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COMPILER OPTIMIZATIONS FOR POWER-AWARE COMPUTING

Georgia Tech Research Corporation

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13. ABSTRACT *(Maximum 200 Words)*
This final report summarizes work done on the DARPA funded project "Compiler Optimizations for Power Aware Computing." Volume I addresses methodologies invented that can be categorized as software based approaches, hardware based approaches and combined software/hardware based approaches. One of the software based approaches, data remapping, showed a 3.1X energy*delay reduction on a realistic example. One of the hardware based approaches, frequency/voltage scaling of second-level memory, showed a 1.3X energy*delay reduction on a realistic example. A combination of data remapping and frequency/voltage scaling of second level memory showed a 2.6X reduction in energy*delay but also showed the lowest power (energy/time) of any of the approaches considered. Volume II addresses realization of the world's first Wearable Motherboard or an intelligent garment for the 21st Century. The motherboard provides an extremely versatile framework for the incorporation of sensing, monitoring, and information processing devices.

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The Wearable Motherboard: A Computational Fabric Architecture for Personalized Mobile Information Processing (PMIP) in Power-Aware Computing

1. BACKGROUND AND RESEARCH OBJECTIVES

Research conducted at Georgia Tech has led to the realization of the world's first Wearable Motherboard™ or an "intelligent" garment for the 21st Century. The Georgia Tech Wearable Motherboard (GTWM) provides an extremely versatile framework for the incorporation of sensing, monitoring and information processing devices. GTWM or the Smart Shirt uses optical fibers to detect bullet wounds, and special fibers, sensors and interconnects to monitor the body vital signs during combat conditions. These fibers serve as *data buses* to carry information to and from the "plugged-in" sensors and information processing devices thus creating a *motherboard* like the one in the computer, except that it is a shirt[1,2].

Although it started off as a "textile engineering" endeavor, the research has led to an even more groundbreaking contribution with enormous implications: the creation of a *wearable integrated information infrastructure* that has opened up entirely new frontiers in personalized information processing, healthcare and telemedicine, and space exploration, to name a few[3]. Until now, it has not been possible to create a personal

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1 The Georgia Tech Wearable Motherboard™: The Intelligent Garment for the 21st Century, http://www.gtwm.gatech.edu.

2 Gopalsamy, C., Park, S., Rajamanickam, R., and Jayaraman, S., "The Wearable Motherboard™: The First Generation of Adaptive and Responsive Textile Structures (ARTS) For Medical Applications", Journal of Virtual Reality, 4:152-168, 1999.

3 Park, S., Gopalsamy, C., Rajamanickam, R., and Jayaraman, S., "The Wearable

information processor that was customizable, wearable and comfortable; neither has there been a garment that could be used for unobtrusive monitoring of the vital signs of humans on earth or space such as temperature, heart rate, etc. In addition to the well-known dimensions of functionality and aesthetics, if 'intelligence' can be embedded or integrated into clothing as a *third dimension*, it would lead to the realization of clothing as a personalized *wearable information infrastructure*. The universal *interface* of clothing will give new meaning to the term "man-machine symbiosis."

1.1 Research Objectives

The overall objective of the research endeavor has been to explore the paradigm of personalized mobile information processing (PMIP) based on a wearable fabric/garment that uniquely blends the characteristics of textile fabrics with capabilities characteristic of computing systems. The investigation of the "*fabric is the computer*" paradigm can lead to the realization of a truly adaptive and responsive wearable computational fabric system, especially in light of the need for power-aware computing systems for military applications. Moreover, such an architecture will eventually lead to these power-aware computing systems being totally mobile – as an integral part of the soldier's uniform – thus resulting in *pervasive* information processing on the battlefield.

Motherboard™: An Information Infrastructure or Sensate Liner for Medical Applications", Medicine Meets Virtual Reality Conference, San Francisco, CA, January 1999, in "Studies in Health Technology and Informatics", IOS Press, Vol. 62, pp. 252-258.

1.2 Key Research Tasks

The major objectives of this project have been accomplished through the following key tasks:

- Design and Development an Architecture for the Computational Fabric;
- Demonstration of the Realization of the Architecture; and
- Identification of Opportunities for Research to Realize the Long-Term Vision of an Individually-Addressable Wearable Information Infrastructure or Computational Fabric**.**

1.3 **Interdisciplinary Research Team**

This research is at the intersection of textiles and computing; therefore, a multidisciplinary team of researchers from Textile Engineering and Computing has been involved in the project. Led by Professor Sundaresan Jayaraman from Textile Engineering, the other members of the research team are: Ms. Sungmee Park, Research Associate in Textile Engineering; and Professors MacKenzie and Ramachandran from the College of Computing. Professor Krishna Palem from Electrical & Computer Engineering was also involved in an advisory role during the initial stages of the project. In addition, undergraduate students Drew Maule and Eric Hudson from the College of Computing, graduate students Ranjeeta Ranjeeta and Jianhong Liang from Textile & Fiber Engineering, and visiting researcher Juan Agudo participated in the research.

1.4 Organization of the Report

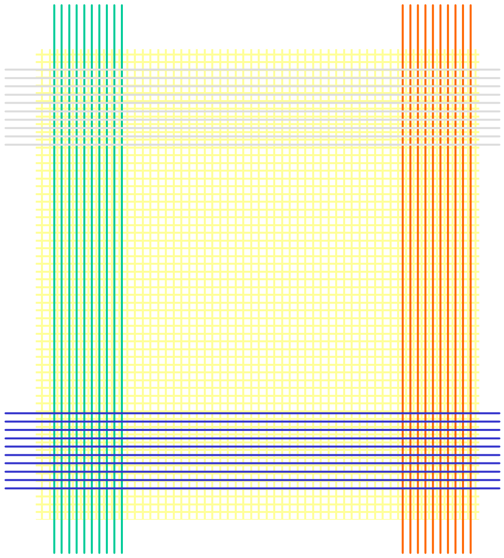
The remainder of the report is organized as follows: In Section 2, the activities related to Task I (Design and Development of the Architecture) are discussed; in Section 3, the activities related to Task II (Demonstration of the Realization of the Architecture) are covered. In Section 4, the vision for "E-Textiles"– a critical step in realizing the paradigm of "Fabric is the Computer" – is laid out. This is followed by a discussion of the fundamental studies carried out on the electrical properties of textile materials. A new concept called "Textillography"– an enabling technology for creating E-textiles – is then presented. In Section 5, the paradigm of "Interactive Textiles" or "*i*-Textiles" that goes beyond "E-Textiles" is presented along with a "framework" for the design and selection of conducting fibers for use in *i*-Textiles. Finally, in Section 6, major presentations and publications associated with the project are covered.

2. DESIGN AND DEVELOPMENT OF AN ARCHITECTURE FOR THE COMPUTATIONAL FABRIC (WEARABLE MOTHERBOARD)

One of the important characteristics of the proposed Computational Fabric is the real-time or event-driven routing of information through the data buses integrated into the Wearable Motherboard (fabric). The current generation of the Wearable Motherboard utilizes “hard” interconnects for routing the information through the fabric. But, to realize the routing of information “on the fly,” there is a need for “soft, programmable” interconnects in the fabric. Therefore, the scope of the effort has been defined to demonstrate PMIP wherein the information from one or more sensors (e.g., Electrocardiogram) is routed through “soft” interconnects in the fabric to the desired output point using FPGAs (field-programmable gate arrays).

2.1 Definition and Realization of the Fabric Infrastructure

The architecture of the fabric infrastructure has been defined in Figure 1. Figure 2 shows the loom set-up to produce the fabric for the realization of PMIP. The fabric consists of typical cotton yarns (white) and colored data buses for carrying the information through the fabric. The electrical, physical and mechanical properties of the conducting yarns can be varied to suit the desired application.



		Material	*EPI	*PPI
DataBus		30 AWG Copper	10	10
Base Fabric		18 Ne Cotton	32	32

* EPI: Ends Per Inch PPI: Picks Per Inch

Figure 1. Architecture of Fabric Infrastructure

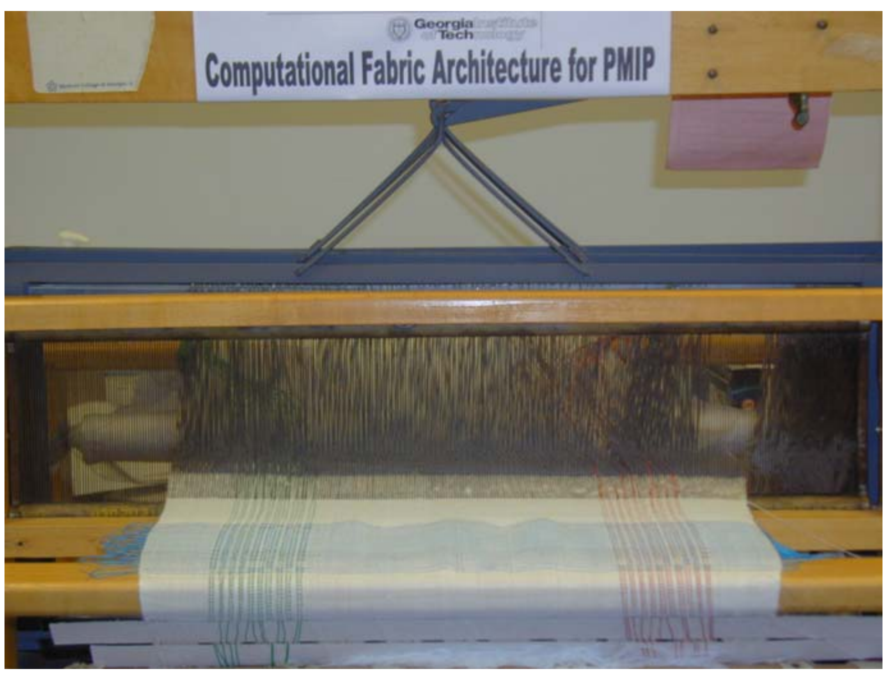


Figure 2. Loom for the Realization of Computational Fabric for PMIP

To explore the feasibility of integration FPGAs into the fabric that will process the information flowing through the data buses in the fabric, technology has been developed to attach "pin–connectors" into the fabric. The process is reliable and lends itself to mass production. This is analogous to the process used in the computing industry to attach connectors to "ribbon cables." Figure 3 shows a pin connector on the right before being integrated into the fabric as shown on the left. This method of using pin connectors will provide a great deal of flexibility in attaching the type of "information processing" device to the connector for the desired activity. Moreover, the modularity will enable the use of multiple types of processors using the same wearable information infrastructure that is an integral part of the fabric. Thus, the user can "plug" in the desired processor/sensor into the fabric and treat the computational fabric as a "motherboard."

Figure 3. Integration of Pin Connectors in the Fabric

2.2 Integration of FPGA onto Fabric Infrastructure

A "switchbox" approach has been chosen to combine the conductive fibers of the computational fabric into a programmable network. The switchbox approach is to treat the conductive fibers like the wiring resources in an FPGA to which switching components can be added at strategic intersections. A key problem in the switchbox architecture is to tolerate loose manufacturing tolerances since there is no *a priori* knowledge of which wires are connected to which pins on the switchbox. Therefore, a design for a single-chip, integrated switchbox has been chosen while, simultaneously, building a demonstration prototype using off-the-shelf components.

2.2.1 <u>The Architecture</u>

The architecture consists of conductive fibers in the fabric infrastructure (textile) plus switchboxes, which are affixed (like buttons) atop intersections of the fibers. The architecture leads to three decisions:

- Placement of switchboxes;
- Complexity of wiring; and
- Complexity of switchboxes.

Placement of Switchboxes: The manufacturing tolerance for placement of switchboxes can be tight or loose.

a. Exact: switchboxes placement tolerance could be good enough to place switchbox contacts atop particular conductive fibers. This option requires precise manufacturing tolerance or a large fiber-to-fiber pitch.

b. Close: the placement tolerance is a small factor larger than the fiber pitch.

c. Random: switchbox placement is uncontrolled.

Since one of the overall objectives of this project is to produce such computational fabrics in a typical manufacturing environment, option (b) has been chosen since it is similar to fastener placement in apparel manufacturing. It is assumed that a switchbox covering several fibers can be placed so that it will contact a particular fiber but it is not known which switchbox contact will actually make the contact.

Complexity of Wiring: The conductive fibers in the computational fabric can be continuous or cut at each switchbox.

a. Continuous fibers are easily manufactured.

b. Cut fibers lead to a richer interconnect with higher local bandwidth between points in the fabric.

From a manufacturing standpoint, option (a) is easier and so fibers that are continuous within the fabric have been chosen. Restricted bandwidth has been addressed by making the switchboxes more capable.

Complexity of Switchboxes: Switchboxes can be built at multiple "grain" sizes, i.e., how much computing resources are concentrated at the intersection of two fibers. Grain sizes are distinguished based on the extent to which the switchbox component participates in topology discovery and configuration.

a. Minimalist, e.g., a single transistor or gate at a single intersection: configuration is managed and performed externally although configuration state may be stored at the intersection, e.g., using technology analogous to floating gates in VLSI.

b. Communication-capable: the switchbox can communicate with, and perform local configuration on behalf of, an external agent. Global configuration is managed externally.

c. Self-configuration-capable: the switchbox contains enough processing power to participate in a distributed, global configuration algorithm.

Option (b) has been chosen with switchboxes capable of self-configuring to the point of establishing communication with an external agent which then manages global configuration.

Thus, the chosen architecture for the computational fabric has electronic elements that are of moderate capability, are placed deliberately, but inexactly, and without making cuts in the fabric.

2.2.2 Technical Issues and Decisions

Three key issues related to the chosen architecture have been identified and solutions have been proposed for them. They are:

- Power Distribution,
- Configuration Information Distribution, and
- Automatic Discovery of Topology.

Power Distribution: Power distribution is difficult with inexact placement of components because power connections are usually distinguished from signal connections. It may be possible to power ordinary integrated circuits via any pin using diode structures similar to existing static discharge protection structures. However, for the first demonstration prototype, power wires are distinguished in the fabric by providing enough spacing to account for the placement tolerance (unlike signal wires).

Configuration Information Distribution: Configuration information distribution is similarly difficult because FPGAs and microcontrollers typically expect configuration information to be presented on specific pins. This problem is not fundamental, however. An FPGA-within-an-FPGA technique has been used to address the problem: A statically-defined FPGA that includes configurable elements within it has been used. Thus it is possible to emulate an FPGA that accepts configuration information from multiple (initially any) pins.

Automatic Discovery of Topology: Topology discovery can be externally or internally managed and sequential or parallel. A conservative approach has been adopted: an external agent sequences the discovery and the discovery proceeds sequentially from the element nearest the external agent.

Thus, the architecture of the computational fabric has been defined and the fabric produced for realizing the architecture.

3. DEMONSTRATION OF THE REALIZATION OF THE ARCHITECTURE

The first step in realizing the architecture through a prototype demonstration has been to define an ideal switchbox element that is buildable using current technology. The next step is the creation of the prototype as an approximation to the ideal device to serve as a proof-of-concept.

3.1 Development of the Hardware Prototype

The ideal device is an EEPROM-based FPGA in a custom plastic package that contains insulation-displacement-style connectors instead of pins. The device would be press-fit onto the fabric like a fastener. Once configured, the device would provide digital communications between points on the fabric including sensors, effectors and communications devices that attach to the switchboxes or directly to conductive fibers that cross a switchbox.

The prototype device is a 2.8"x1.8" proto-board containing a small EEPROM-based FPGA (Altera EPM7160S) plus a microcontroller (Motorola HC11) as shown in Figures 4 and 5. The board connects to the fabric using two standard 26-pin insulation-displacement connectors (IDCs) ordinarily used for ribbon cable.

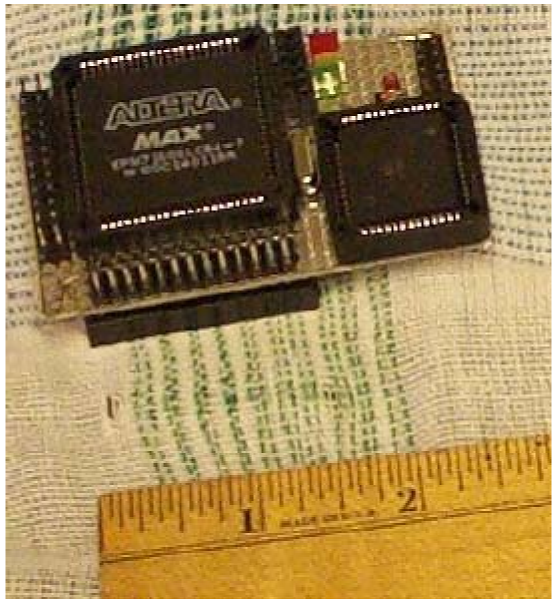


Figure 4. Prototype board, 2.8"x1.8", containing the FPGA and microcontroller, Site- specific sensor/effector/communication devices attach as "daughtercards."

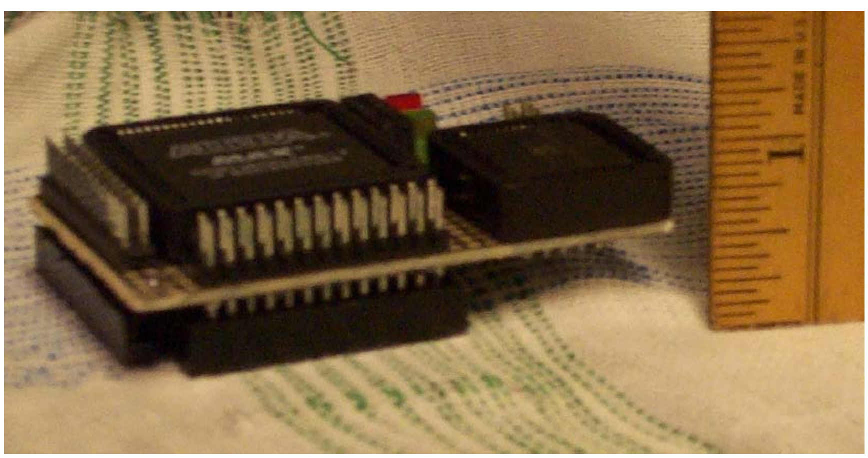


Figure 5. Side view of prototype showing the insulation displacement connectors contacting conductive fibers (in color) in the fabric.

The fabric shown in Figure 6 contains conductive fibers at a density of 10 per inch. The 26-pin IDCs contain contacts at a pitch of 20 to the inch. Every fiber makes contact with some contact in the connector but the position of that contact is off by up to two positions in the connector. In the connector, the leftmost and rightmost fibers are dedicated to power buses while the center fibers carry signals, up to seven signals in each direction. The chosen FPGAs were physically integrated into the fabric (see Figure 7).

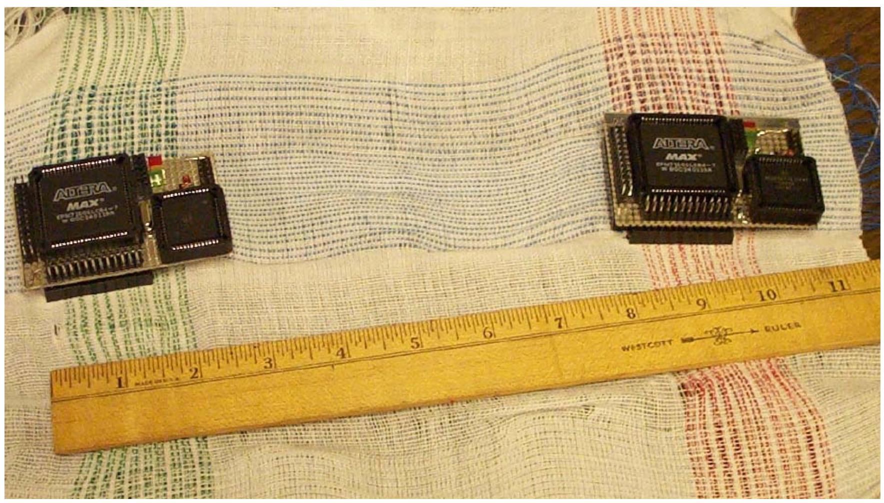
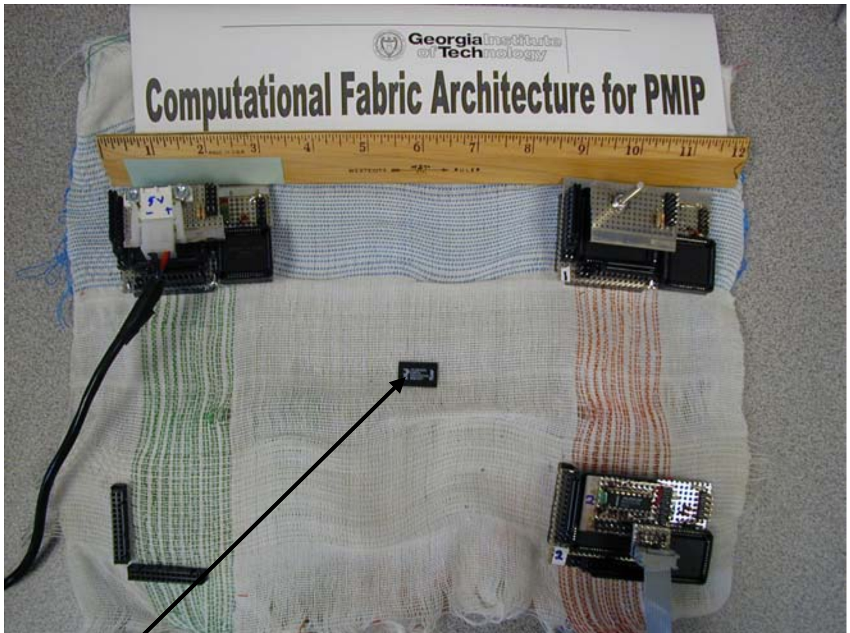


Figure 6. The fabric includes conductive fibers at a density of 10 per inch. Up to seven signals are available in each direction to each switchbox element.



Ideal Size of Computational
Hardware in a Fabric

Figure 7. The PMIP Network in a Fabric

3.2 Development of Software Module

The next step in the realization of the PMIP Architecture has been the development and implementation of the software for the hardware prototype. One of the FPGAs communicated with an external agent (a Linux-based personal computer) that was responsible for managing the global configuration of the FPGAs in the fabric by sequencing the "discovery" in the fabric beginning with that initial FPGA.

Two software modules have been created; the first "demonstrates" the pin-connection discovery algorithm implemented in the system to identify the connections between the various pins on the FPGAs in the fabric and to display the connection paths (see Figures 8 and 9). This enables discovery of the interconnects *on the fly* after the manufacturing has been carried out and there is no *a priori* knowledge of the specific connections between the elements in the fabric. The second module discovers the connections and displays the paths on the screen as the discovery process proceeds when the FPGA is powered.

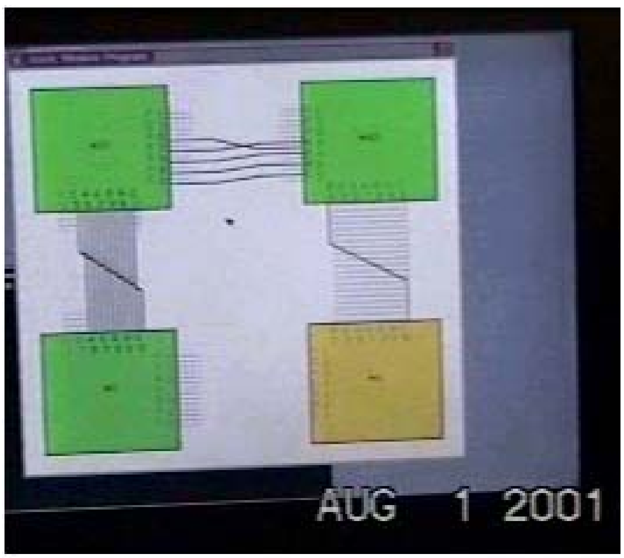


Figure 8. Demonstration of Discovery of Pin-Connection on the FPGAs in the Computational Fabric (In-Process View)

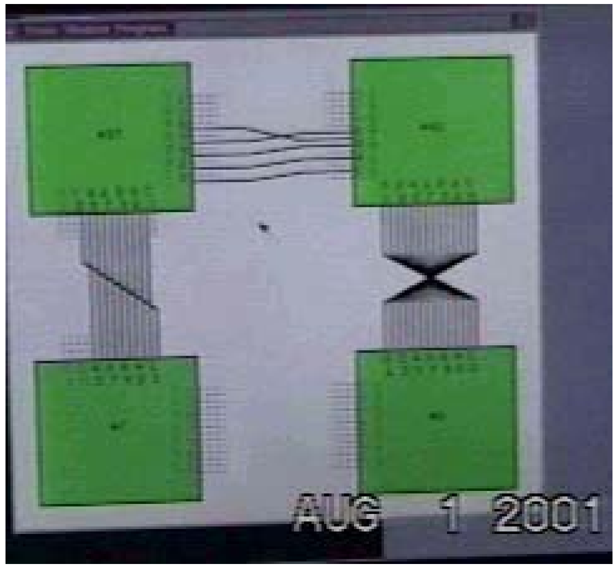


Figure 9. Demonstration of Discovery of Pin-Connection on the FPGAs in the Computational Fabric (Completed View)

To demonstrate the flow of information in the fabric network through the soft interconnects, a potentiometer was attached as a daughterboard to one of the FPGAs. Whenever it was “twiddled” (see Figure 10), the resulting change was displayed on the screen (Figures 11 and 12).

Thus, the PMIP architecture defined in Section 2 has been realized and successfully demonstrated in a fundamental prototype.

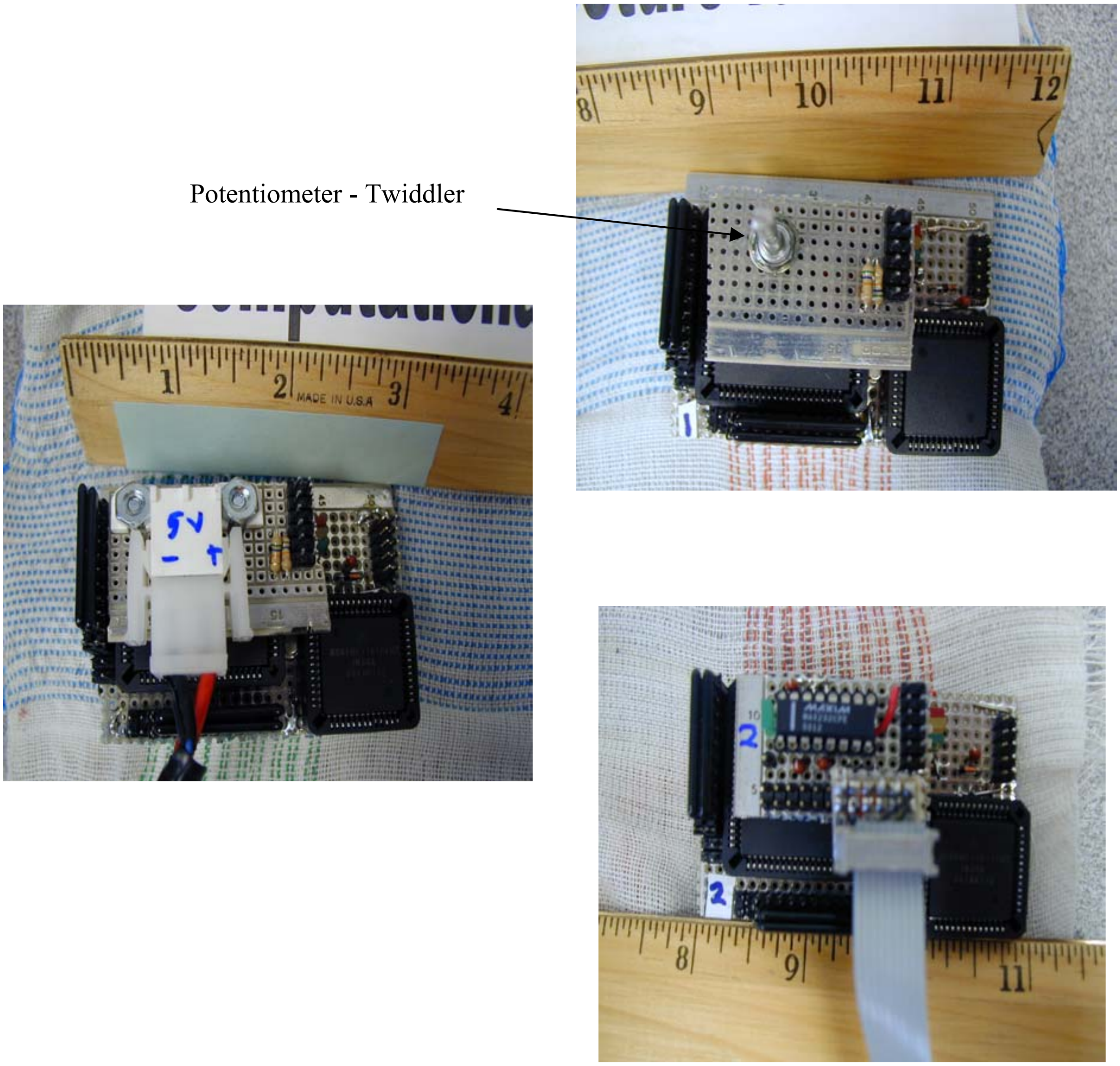


Figure 10. The Various Elements on the PMIP Fabric

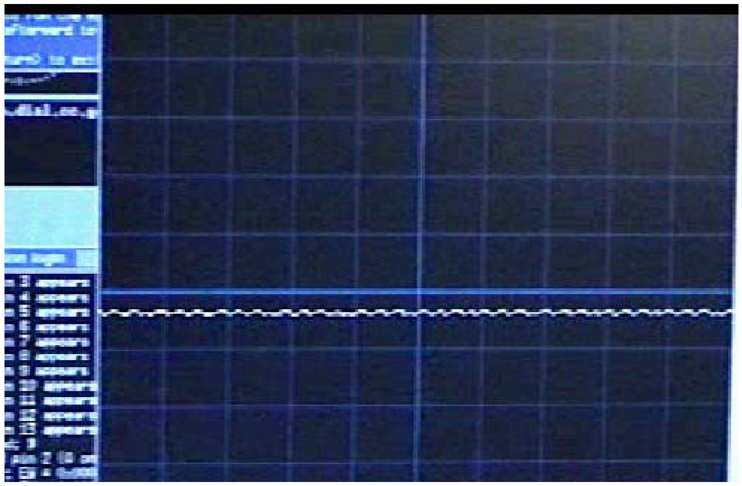


Figure 11. The Steady State Display

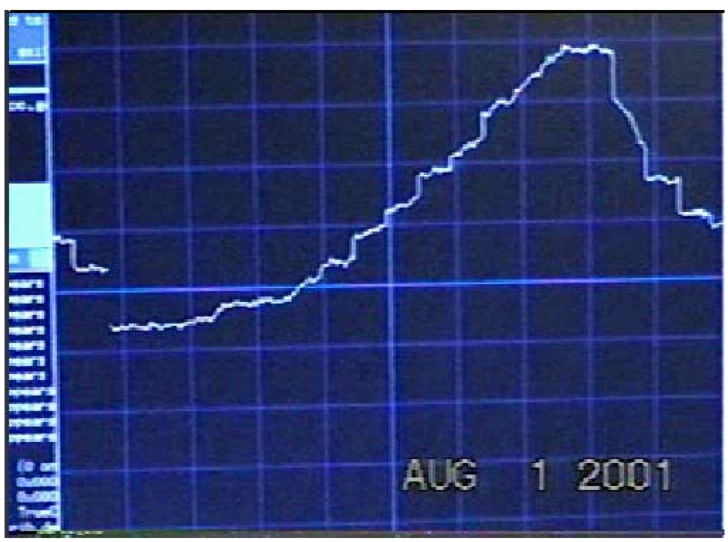


Figure 12. Flow of Information through the PMIP Fabric.

4. FABRIC IS THE COMPUTER: VISION AND FUNDAMENTAL RESEARCH

Figure 13 depicts our vision for electronic or E-Textiles, i.e., the paradigm of "fabric is the computer." The major facets illustrate the various "building blocks" of the system that must be seamlessly integrated to realize the vision, starting with the underlying physical fabric or "*Platform*." The design of this platform or infrastructure involves the exploration of materials, structures and manufacturing technologies. The second key facet for realizing this paradigm of a true computational *fabric* is the "*Interconnect Architecture*" in the fabric, which involves the design and incorporation of physical data paths and interconnection technologies, i.e., the realization of "textile electrical circuits." Integration of sensors, microchips and other devices (e.g., for communication and control) is critical for the realization of an "intelligent" E-Textiles for *any* application, say for example, battlefield management, and therefore, "*Hardware Integration*" constitutes the third facet or building block shown in Figure 13. Issues related to information processing such as fault tolerance in light of manufacturing defects and Quality of Service (QoS) *within* the E-Textile and *between* the E-Textile and external agents/devices are critical for the incorporation and optimal utilization of computing resources, and therefore, "*Software*" is the fourth facet of the E-Textile continuum. And finally, as shown in the figure, a set of underlying *performance metrics* ranging from the physical dimensions (of the resulting structure/system) to costs, manufacturability and data flow rates must be utilized to assess the successful realization and performance of the desired E-Textile. Thus this paradigm of "fabric is the computer" represents a fascinating area of research that necessitates collaboration amongst scientists and engineers from a variety of disciplines including textiles, computing and communications, sensor technologies and application domains (e.g., medicine, space, military).

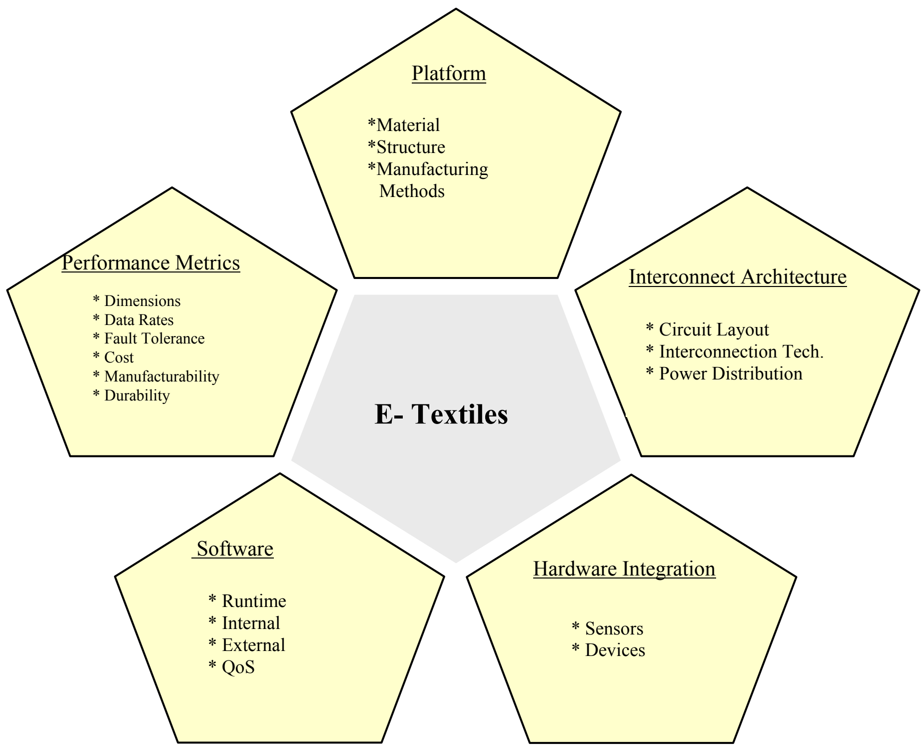


Figure 13. The E-Textiles Vision

This vision of E-Textiles has been used to investigate techniques and technologies in the first two facets, viz., Platform and Interconnection Architecture, respectively, and to lay the foundation for this field of research.

4.1 The E-Textiles Platform: Investigation and Characterization of Materials

The characterization of materials is important for the selection of the right materials – yarns/fabrics with the desired sensing/processing characteristics *and* textile properties – to serve as conducting elements in E-Textiles. Therefore, another aspect of the work focused on engineering and testing yarns and fabrics with desired properties for use in the E-Textiles platform or PMIP class of structures. This work has been carried out partly in collaboration with fiber/yarn vendors. One of the key issues affecting the use of conductive fibers in textile structures is electromagnetic interference, especially since the linear densities and diameters of these yarns are different from typical shielded wires and cables used in practice for connecting electrical/electronic devices. Therefore, research has been carried out to shield conductive yarns using traditional spinning processes to minimize such electrical interference. In the trials, the density of the fibers used to shield the conductive yarns was varied to produce different yarn structures that were flexible so that they could still be used in producing fabrics for PMIP.

4.1.1 Characterization of Conductive Yarns

A series of experiments has been designed to test the effects of:

- yarn material type (all yarns *with* and *without* insulation);
- signal frequency (210Hz to 1010Hz);
- applied voltage (1.3V to 1.9V);

- type of deformation (Constant Rate of Loading, Constant Rate of Elongation); and
- tensile strain rate (0% to breaking strain)

on the electrical and tensile properties of conductive yarns (see Figure 14 and 15).

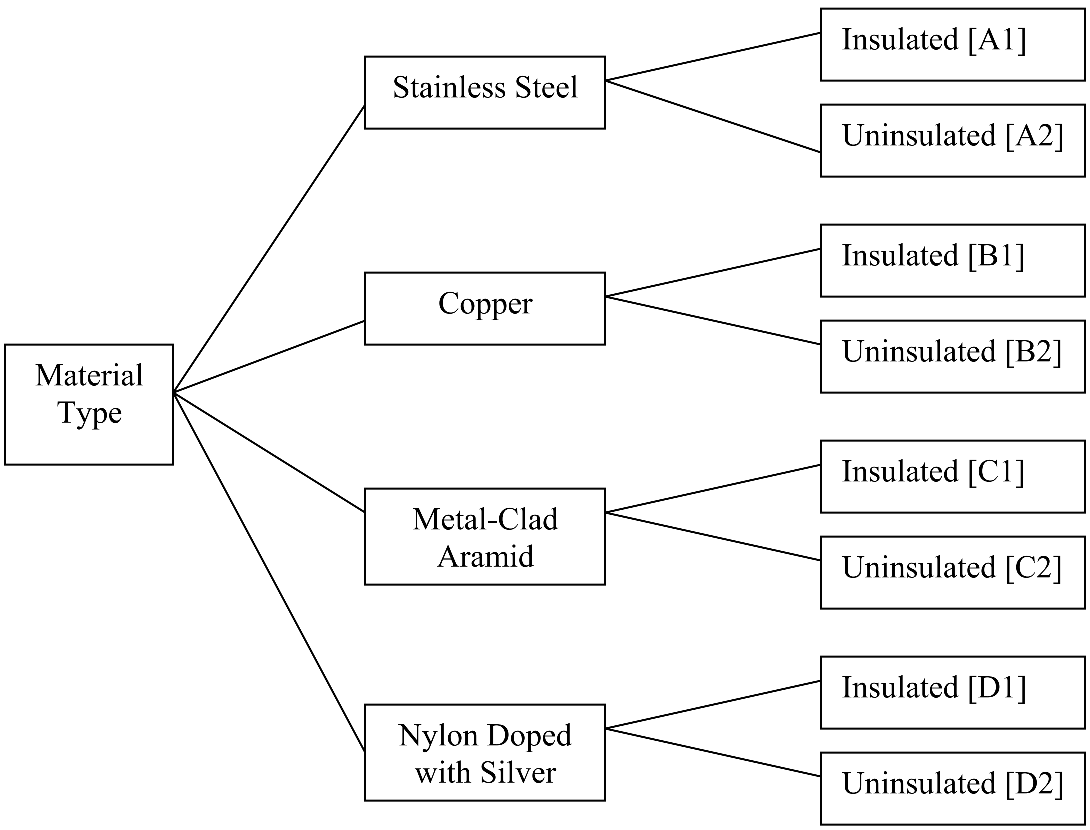


Figure 14. Spectrum of Material Types

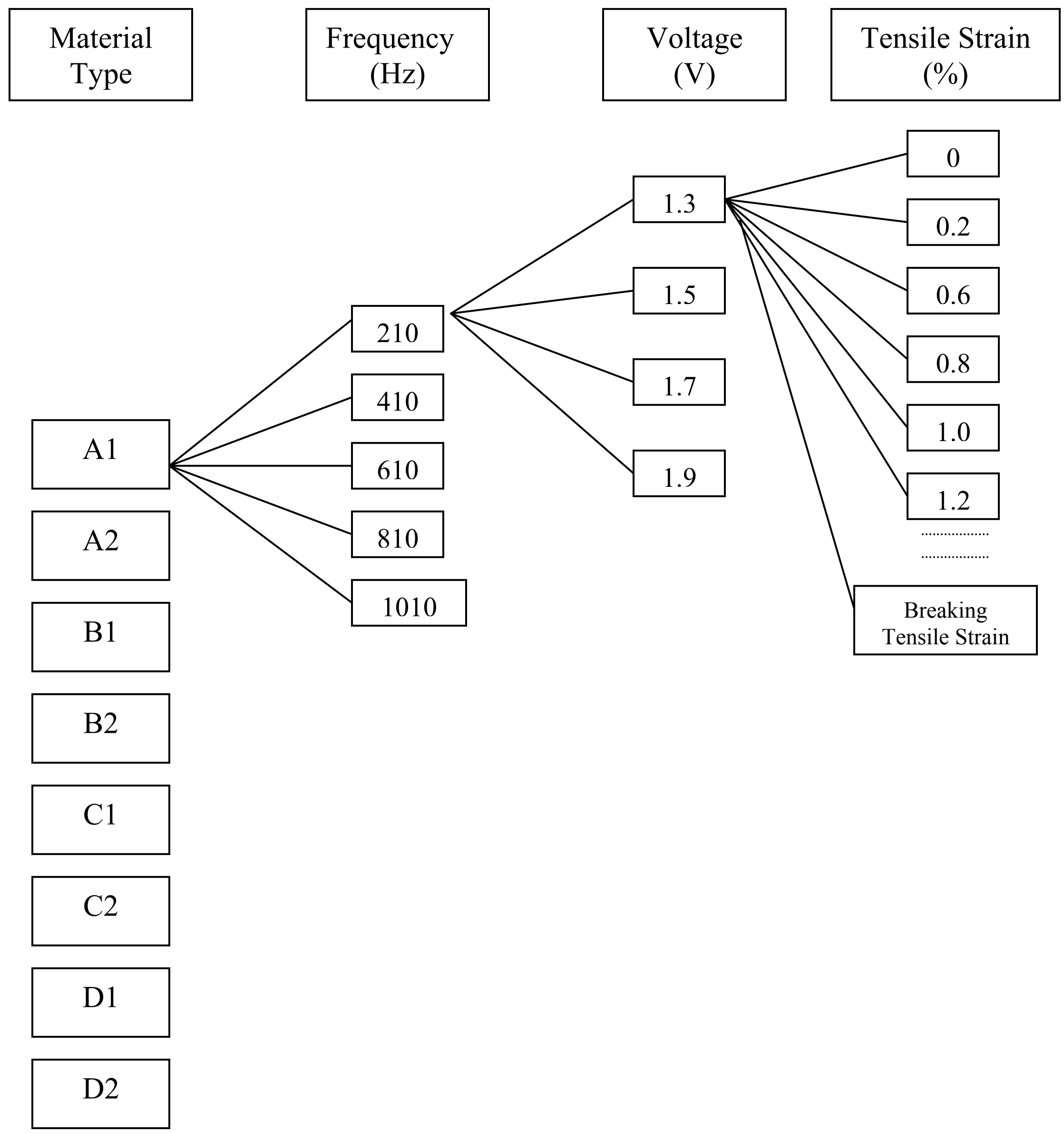


Figure 15: Test Specimens and Conditions

4.1.1.1 Test Methods

ASTM D-2256 Test Method was used for the tensile test using the Instron tester. Initially, both Constant Rate of Loading (CRL) and Constant Rate of Elongation (CRE) methods were used. Since there was no difference in the results from the two methods, the CRE (10 mm/min) method was adopted for the study. As per the ASTM standard, three tests were carried out for each test sample with a gauge length of 250 mm.

The following instruments were used in carrying out the tests:

- Instron 5567 Tensile Tester
- HP Multimeter (HP 34401A)
- HP Function Generator (HP 33120A)
- Oscilloscope (HP 54615B)
- VEE Software System

4.1.1.2 Testing Set-up for Electrical Properties

Figure 16 shows the schematic of the initial set-up used in the study of the electrical properties of the yarns. As shown in the figure, a function generator, an external resistor and the candidate yarn were connected in series. An oscilloscope was connected to assess the role of inductance and capacitance of the test yarn. There was no phase delay between the two probes of the oscilloscope indicating that there was no effect of inductance or capacitance on the yarn. Therefore, the test yarns were considered to be pure resistors.

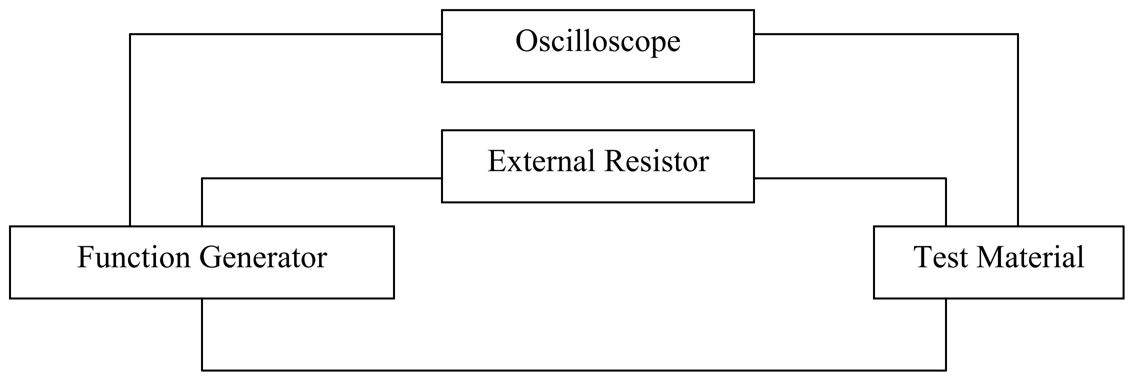


Figure 16. Schematic Drawing of Inductance and Capacitance Testing

Figure 17 shows the schematic of the final set-up used in assessing the electrical properties of the yarns. The internal resistance of the multimeter has an important effect on the measurements at low currents and frequencies. Therefore, an external resistor similar in value to the resistance of the yarn is used to minimize the errors due to such internal resistance of the instrument.

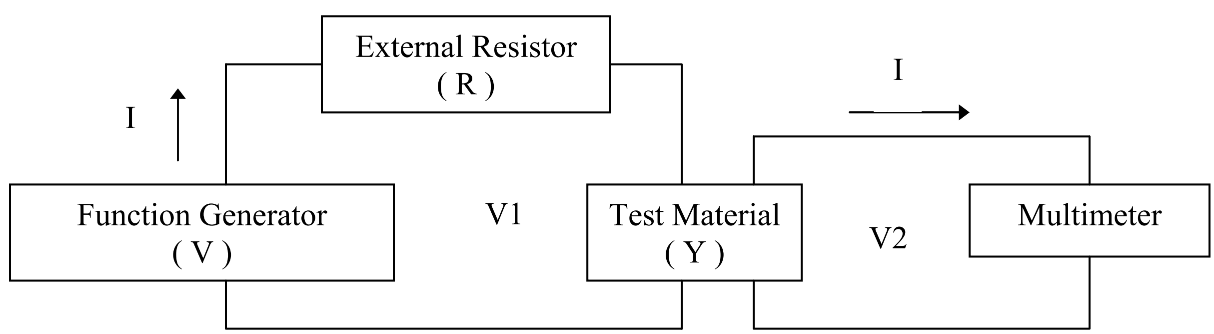


Figure 17. The Test Set-up for Electrical Properties of Yarns and Fabrics

4.1.1.3 Testing Set-up: Tensile Strain and Electrical Properties of Yarns and Fabrics

Figure 18 shows the experimental set-up for testing the effect of tensile strain on the electrical properties of conductive yarns and yarns woven into fabrics.

Figure 18. Effect of Tensile Strain on Electrical Properties: Overview of Set-up

Figure 19 shows the test sample mounted on the Instron tester; its ends are connected to the electrical instruments depicted earlier in Figure 17.

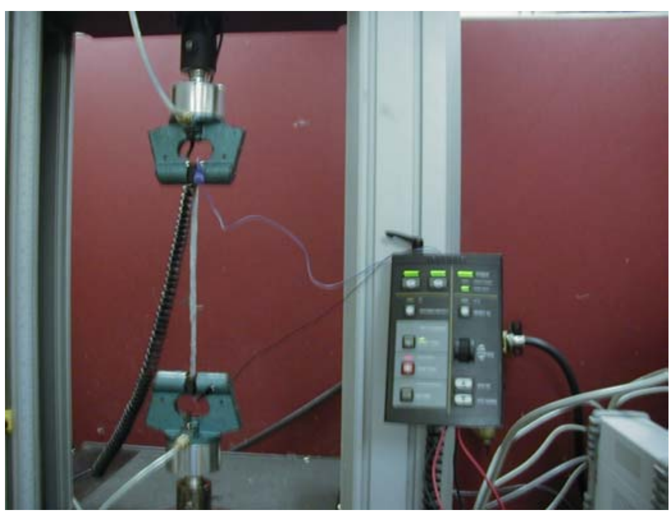


Figure 19. Test Sample mounted on the Instron Tester.

4.1.1.4 Results and Discussion: Electrical Properties of Yarns

Table 1 shows the summary of results of the range of tests on the yarn samples (see Figure 14 for explanation of material types). The values represent the average of three test specimens per sample (see ASTM D-2256 for details).

Table 1. Summary of Yarn Test Results

Material	Linear Density	Resistance at 0%	Resistance at Break[4]	Breaking Tensile Strain	Breaking Load	Tenacity
	Tex (Ne)	Ohm	Ohm	%	Kgf	g/tex
A1	256 (2.3)	17.70	17.8	1.23	2.14	8.36
A2	107 (6)	22.14	24.9	1.27	2.04	19.07
B1	724 (0.8)	0.26	0.28	9.8	1.67	2.31
B2	448 (1.3)	0.27	0.33	29.93	1.3	2.90
C1	416 (1.4)	0.84	0.85	2.16	6.73	16.18
C2	144 (4)	1.3	1.42	2.79	3.44	23.89
D1	137 (4)	88.89	593.69	19.13	1.53	11.17
D2	40 (15)	60.66	982.66	30.57	0.89	22.25

[4] The resistance of the material is calculated using Ohm's Law and the set of equations (Figure 17):

$V_1=I*(R+Y)$
$V_2=I*Y$

$V_1 / V_2 = I * (R+Y) / I * Y$

Therefore, $Y = RV_2 / (V_1-V_2)$

Where
V_1: The voltage from Function Generator,
V_2: The voltage measure on the multimeter,
R: The external resistor,
Y: The resistance of the yarn,
I: The current in the circuit.

Stainless Steel (Material A)

Effect of Tensile Strain on Insulated Yarn

- There is no significant effect of tensile strain on the resistance of insulated stainless steel yarns when the strain is increased from 0% to breaking strain (1.23%) as shown in Figure 20.

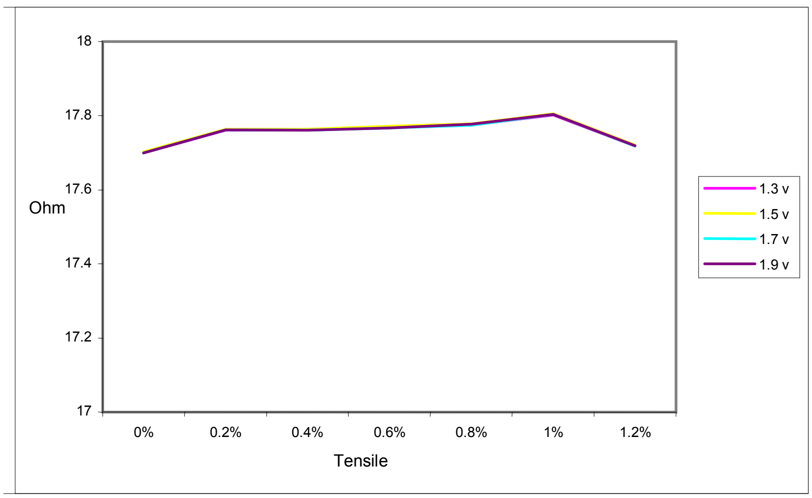


Figure 20. Resistance of Insulated Stainless Steel Yarn at different Tensile Strains

* At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated stainless steel yarns (Figures 21 and 22).

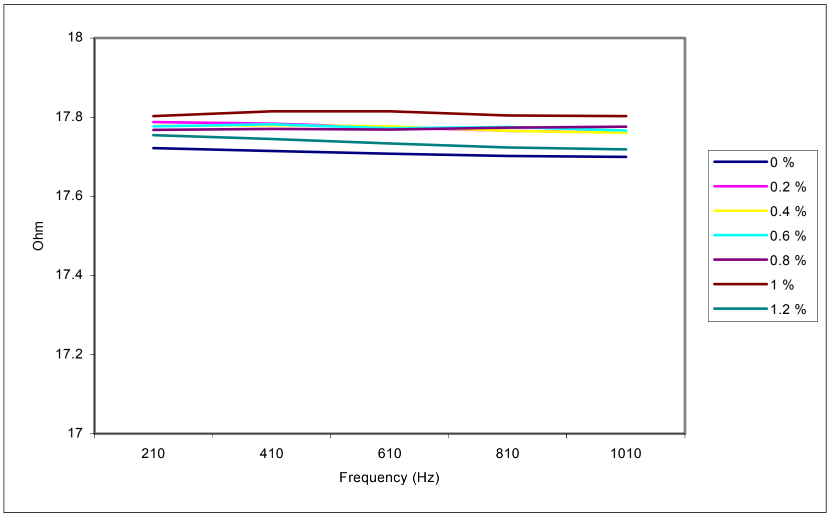


Figure 21. Resistance of Insulated Stainless Steel Yarn at different Frequencies

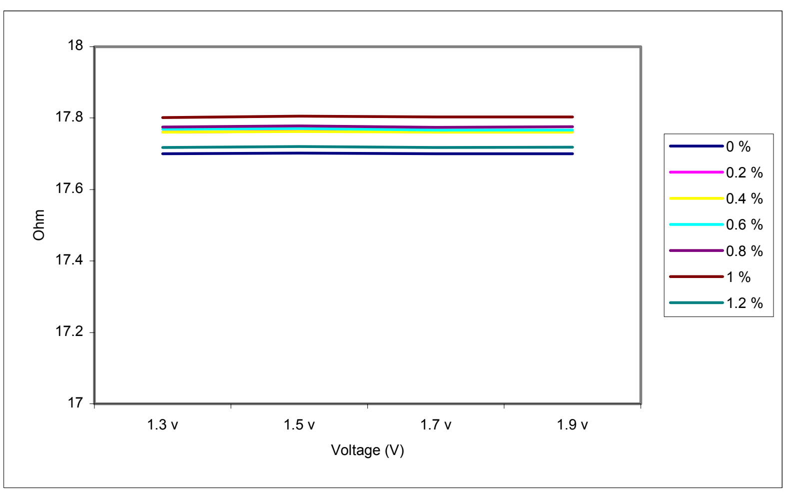


Figure 22. Resistance of Insulated Stainless Steel Yarn at different Applied Voltages

Effect of Tensile Strain on Uninsulated Yarn

- The resistance of the uninsulated stainless steel yarn doesn't change when the tensile strain changes from 0.2% to 1.2% at different voltages. However, as shown in Figure 23, the resistance increases by nearly 5% in the range 1.2% - breaking strain (1.27%). This interesting behavior – in contrast to the insulated yarn – may be attributed to the difference in the modes of deformation of the two yarns. In the case of the uninsulated yarn, the fibrous strands in the yarn are probably retaining electrical connectivity – the result of a "non-catastrophic" failure of the yarn – while the insulated yarn is experiencing a catastrophic failure. The former causes "thinning" of the yarn leading to an increase in the resistance, while that phenomenon doesn't occur in the case of the insulated yarn. Note, however, that this strain range before break must be closely studied to confirm this behavior.

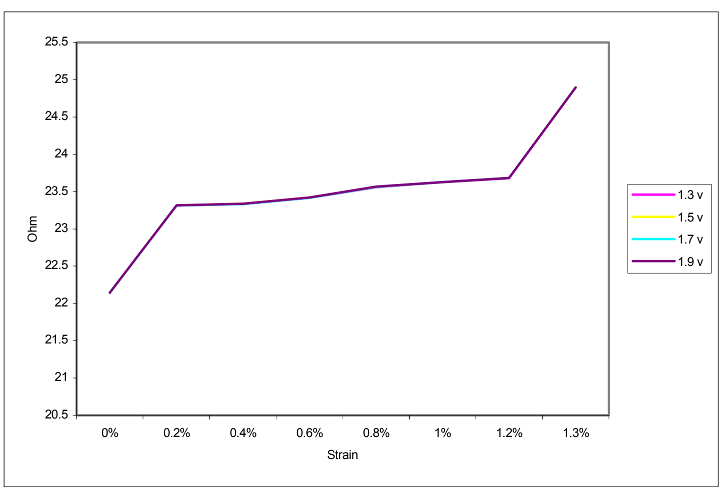


Figure 23. Resistance of Uninsulated Stainless Steel Yarn at different Tensile Strains and Voltages

- As shown in Figures 24 and 25 there is no significant effect of frequency and voltage on the resistance of uninsulated stainless steel yarns at any given tensile strain.

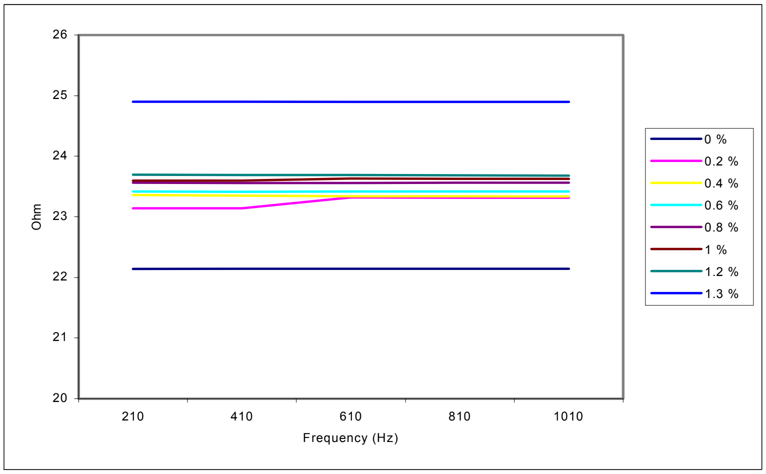


Figure 24. Resistance of Uninsulated Stainless Steel Yarn at different Frequencies

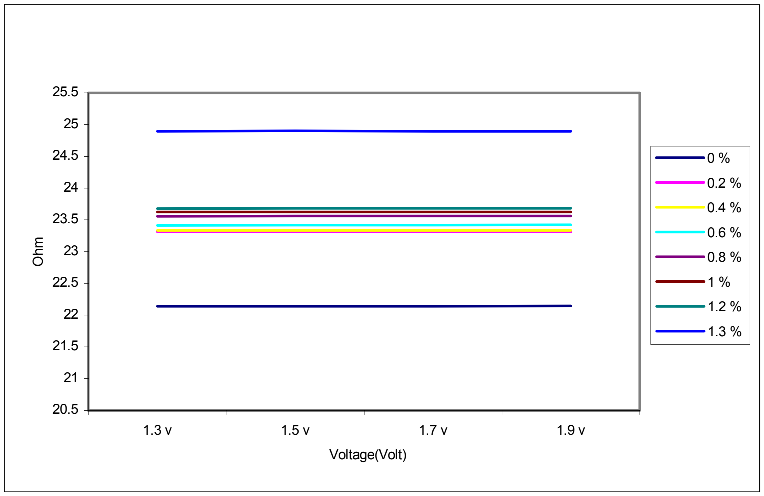


Figure 25. Resistance of Uninsulated Stainless Steel Yarn at different Voltages

Copper (Material B)

Effect of Tensile Strain on Insulated Yarn

- There is no significant effect of tensile strain on the resistance of insulated copper yarns when the strain is increased from 0% to breaking strain (9.8%) at different voltages as shown in Figure 26.

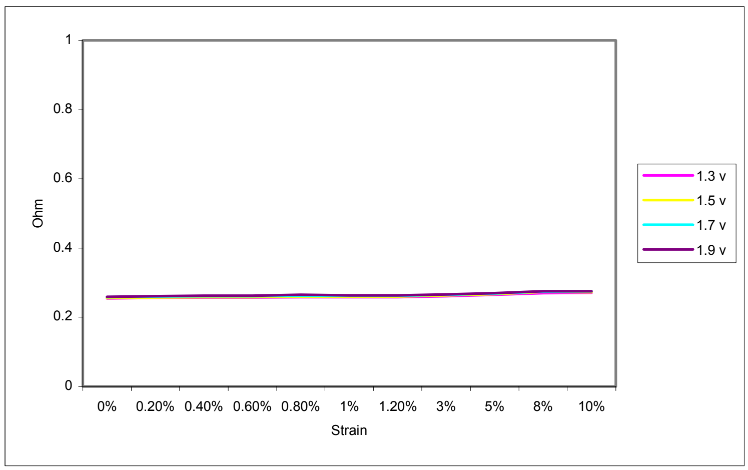


Figure 26. Resistance of Insulated Copper Yarn at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated copper yarns (Figures 27 and 28).

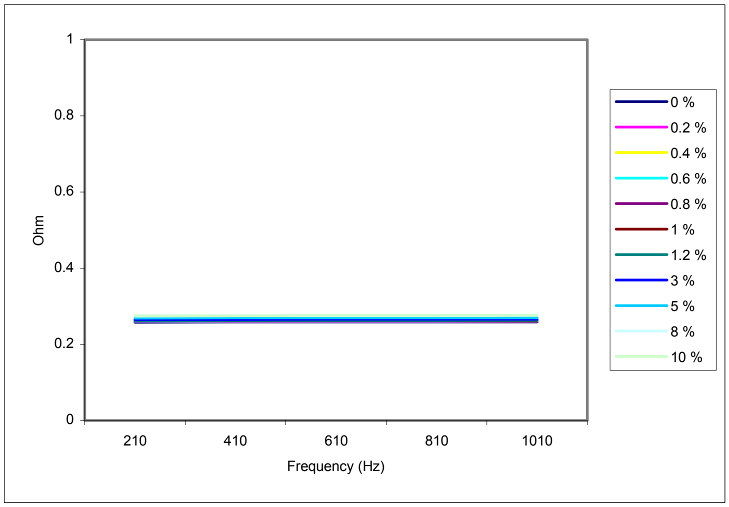


Figure 27. Resistance of Insulated Copper Yarn at different Frequencies

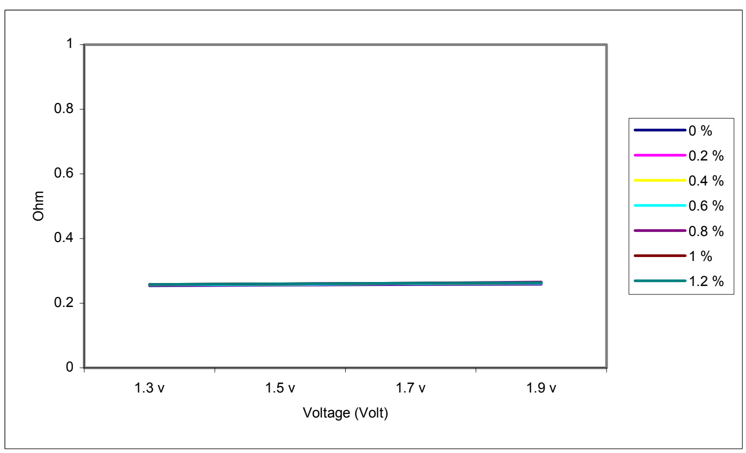


Figure 28. Resistance of Insulated Copper Yarn at different Voltages

Effect of Tensile Strain on Uninsulated Yarn

- There is no significant effect of tensile strain on the resistance of uninsulated copper yarns when the strain is increased from 0% to breaking strain (29.93%) at different voltages as shown in Figure 29.

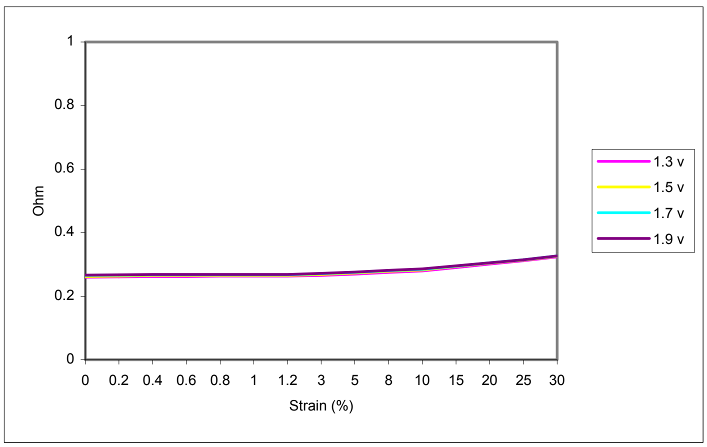


Figure 29. Resistance of Uninsulated Copper Yarn at different Tensile Strains

• At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of uninsulated copper yarns (Figures 30 and 31).

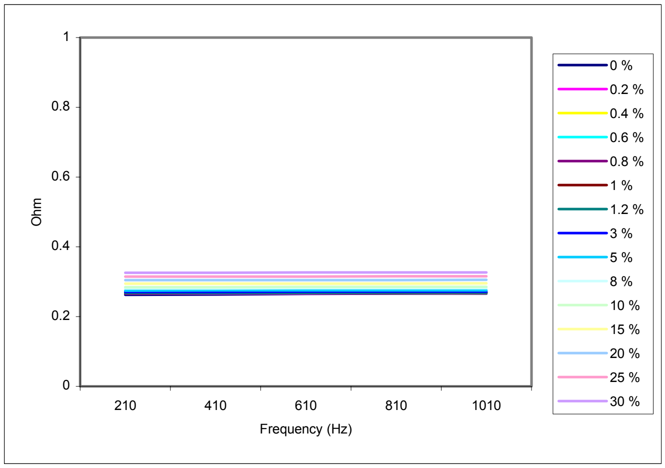


Figure 30. Resistance of Uninsulated Copper Yarn at different Frequencies

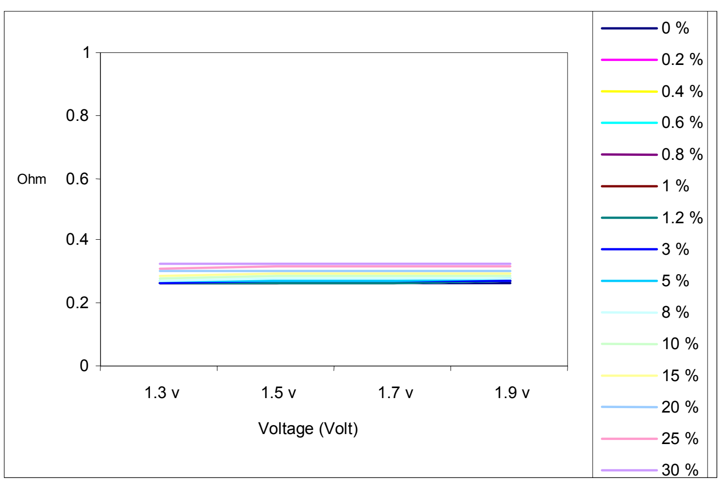


Figure 31. Resistance of Uninsulated Copper Yarn at different Voltages

Metal-Clad Aramid (Material C)

Effect of Tensile Strain on Insulated Yarn

- There is no significant effect of tensile strain on the resistance of insulated metal-clad Aramid yarns when the strain is increased from 0% to breaking strain (2.16%) at different voltages as shown in Figure 32.

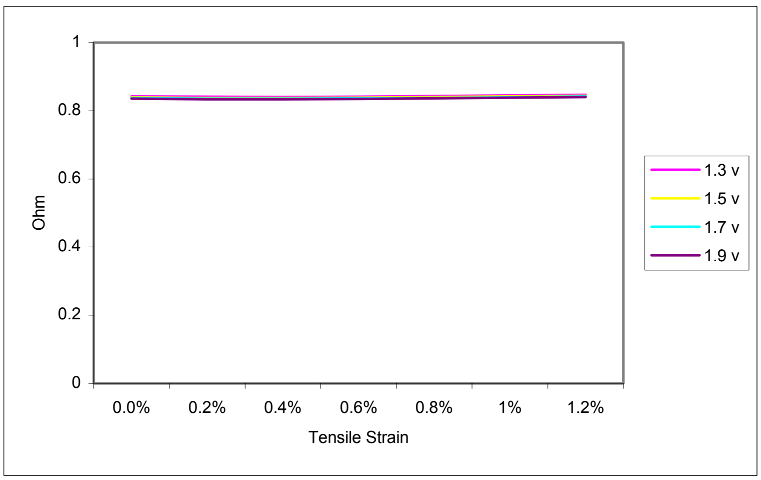


Figure 32. Resistance of Insulated Metal-Clad Aramid Yarn at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated metal-clad Aramid yarns (Figures 33 and 34).

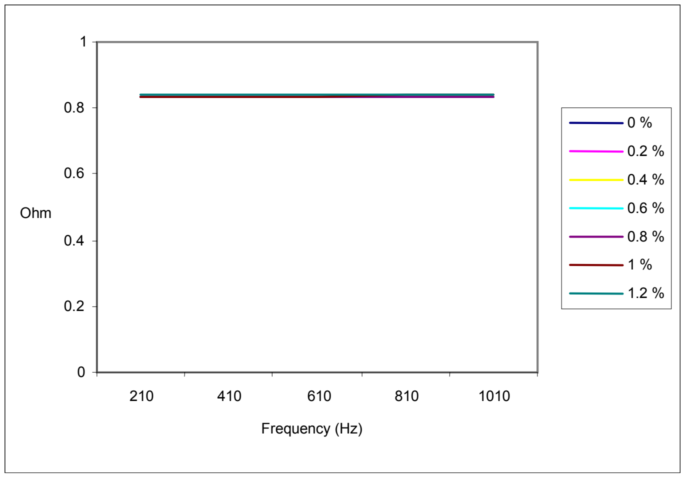


Figure 33. Resistance of Insulated Metal-Clad Aramid Yarn at different Frequencies

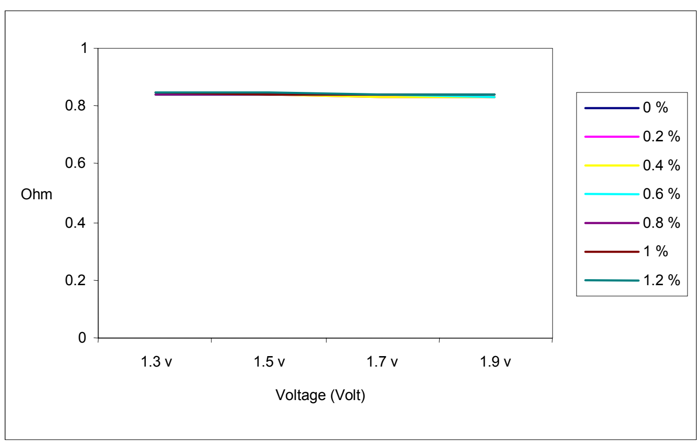


Figure 34. Resistance of Insulated Metal-Clad Aramid Yarn at different Voltages

Effect of Tensile Strain on Uninsulated Yarn

- The resistance of the uninsulated metal-clad Aramid yarn increases by 16% as tensile strain changes from 0.2% to breaking strain (2.79%) at different voltages as shown in Figure 35. This behavior, i.e., change in resistance with tensile strain is in contrast to the insulated yarn and may be attributed to the difference in the modes of deformation of the two yarns. In the case of the uninsulated yarn, the fibrous strands in the yarn are probably retaining electrical connectivity – the result of a "non-catastrophic" failure of the yarn – while the insulated yarn is experiencing a catastrophic failure. The former causes "thinning" of the yarn leading to an increase in the resistance, while that phenomenon doesn't occur in the case of the insulated yarn.

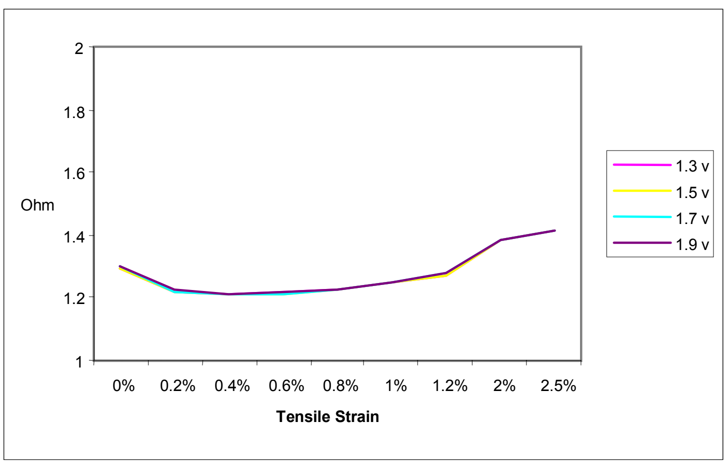


Figure 35. Resistance of Uninsulated Metal-Clad Aramid Yarn at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of uninsulated metal-clad Aramid yarns (Figures 36 and 37).

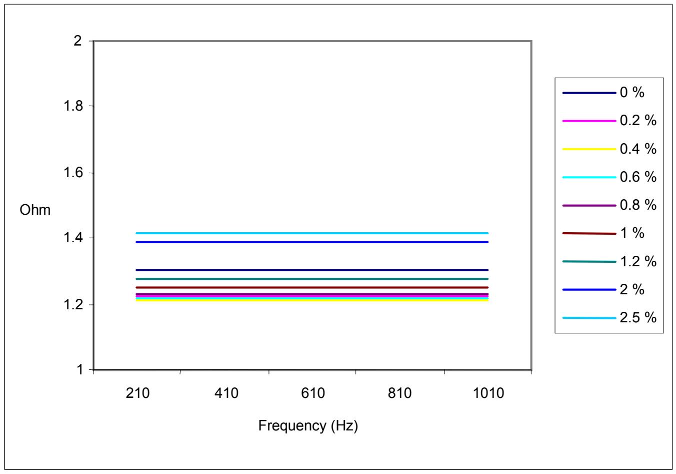


Figure 36. Resistance of Uninsulated Metal-Clad Aramid Yarn at different Frequencies

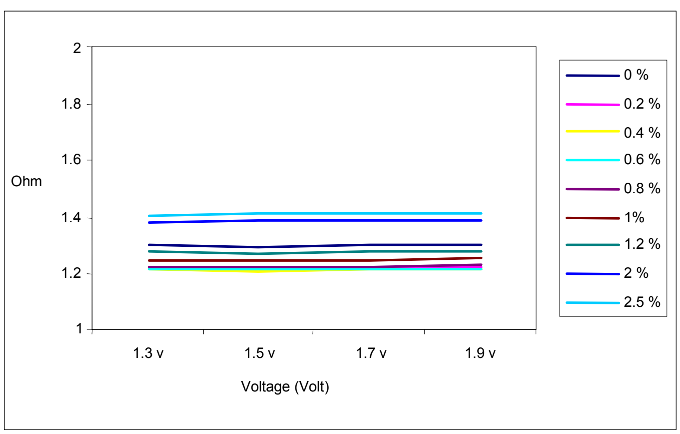


Figure 37. Resistance of Uninsulated Metal-Clad Aramid Yarn at different Voltages

Nylon Doped with Silver (Material D)

Effect of Tensile Strain on Insulated Yarn

- There is a significant effect of tensile strain on the resistance of insulated Nylon doped with silver yarns when the strain is increased from 0% to breaking strain (19.13%) at different voltages. As shown in Figure 38, the resistance is approximately 88 Ohm from 0% to 1.2% tensile strain; it then increases gradually to 587 Ohm at break – a significant increase of 560%. This increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain, depending on processing conditions).

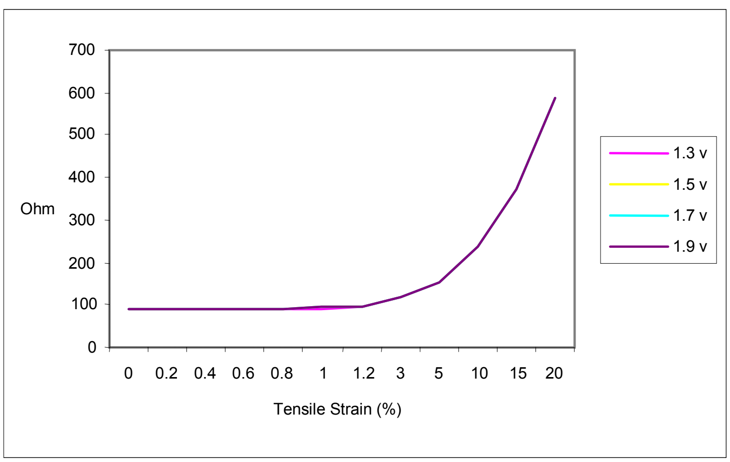


Figure 38. Resistance of Insulated Nylon Doped with Silver Yarn at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated Nylon doped with silver yarns (Figures 39 and 40).

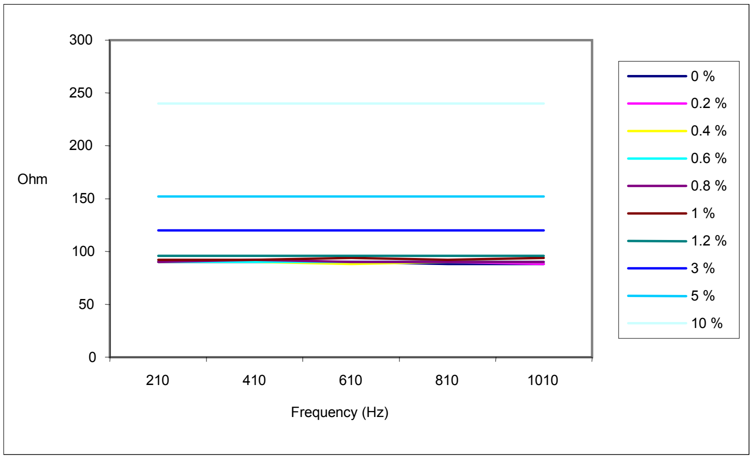


Figure 39. Resistance of Insulated Nylon Doped with Silver Yarn at different Frequencies

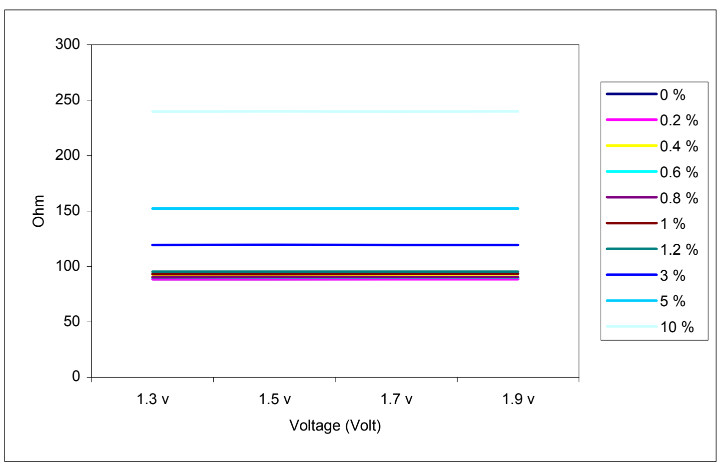


Figure 40. Resistance of Insulated Nylon Doped with Silver Yarn at different Voltages

Effect of Tensile Strain on Uninsulated Yarn

- There is a significant effect of tensile strain on the resistance of uninsulated Nylon doped with silver yarns when the strain is increased from 0% to breaking strain (30.57%) at different voltages. The resistance changes from 61 Ohm at 0% strain to 67 Ohm at 1.2% tensile strain – an increase of 8%. It then increases gradually, but at a higher rate, to 983 Ohm at break – a remarkable increase of 1520% (Figure 41). This increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain, depending on processing conditions). The role of the insulation in "damping" the effect of the base yarn properties on the resistance of yarn is clear from the differences in the increases in the resistance for the two yarns, viz., 560% and 1520%, respectively. This means the uninsulated yarn was "less" constrained by the insulation – an important consideration when designing yarns for E-Textiles.

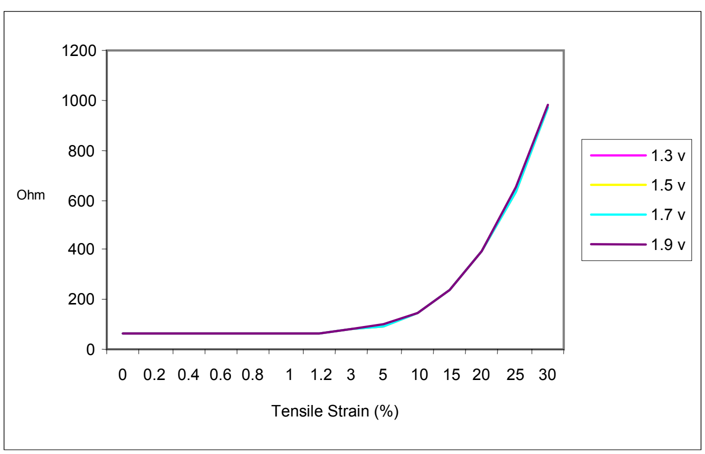


Figure 41. Resistance of Uninsulated Nylon Doped with Silver Yarn at different Strains and Voltages

At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of uninsulated Nylon doped with silver yarns (Figures 42 and 43).

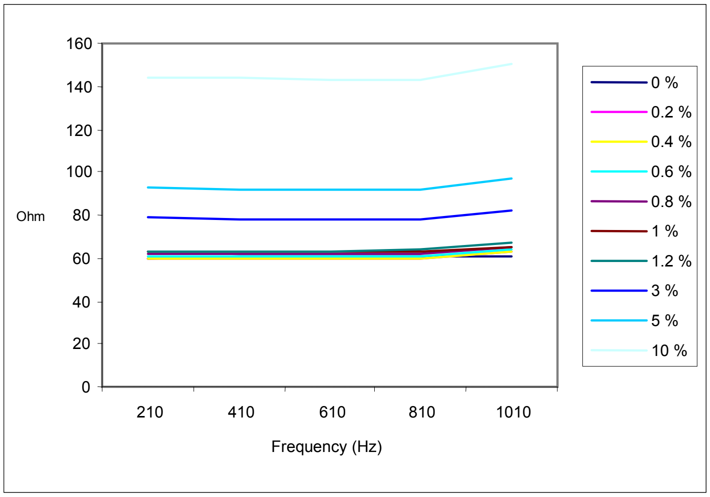


Figure 42. Resistance of Uninsulated Nylon Doped with Silver Yarn at different Frequencies

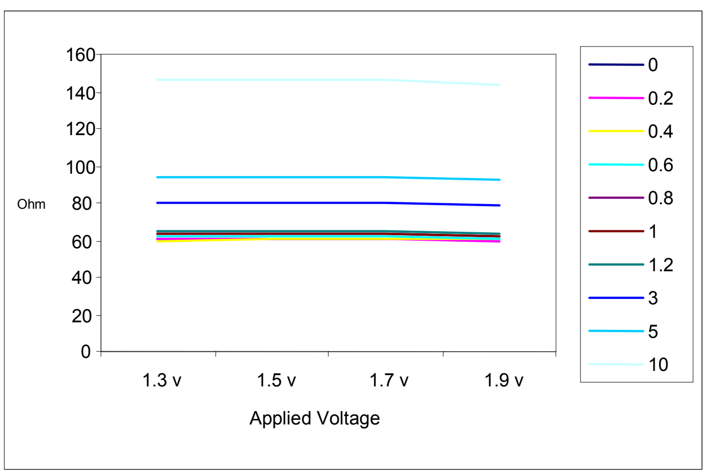


Figure 43. Resistance of Uninsulated Nylon Doped with Silver Yarn at different Voltages

4.1.1.5 Summary of Electrical Properties of Conductive Yarns

Table 2 shows a diagrammatic representation of the effects of tensile strain, frequency and voltage on the electrical resistance of insulated and uninsulated conductive yarns, a key element in E-Textiles.

Table 2. Diagrammatic Representation of Electrical Properties of Materials

Material Type		Effect of Tensile Strain On Resistance of Yarns	Effect of Frequency On Resistance of Yarns	Effect of Voltage On Resistance of Yarns
Stainless Steel	Insulated	↔	↔	↔
	Uninsulated	↑	↔	↔
Copper	Insulated	↔	↔	↔
	Uninsulated	↔	↔	↔
Metal Clad Aramid	Insulated	↔	↔	↔
	Uninsulated	↑	↔	↔
Nylon doped with Silver	Insulated	↑↑	↔	↔
	Uninsulated	↑↑	↔	↔

<u>Notation:</u>

↔	↑	↑↑
No Change	Increase	Significant Increase

Effect of Yarn Structure on the Resistance of Materials

Stainless steel, metal-clad Aramid and Nylon-doped yarn are multifilament yarns while the copper fiber has a “solid” structure. This difference in the basic structures is reflected in the response of the insulated and uninsulated yarns in the two classes to tensile deformation, and hence resistance: The resistance of the uninsulated stainless steel, Aramid and Nylon-doped fibers increases with tensile strain while that of the uninsulated copper yarn remains the same with increase in tensile strain.

Effect of Insulation on Tensile Properties of all Materials

As seen in Table 1, the tenacity of the uninsulated yarn is higher than that of the insulated yarn. This difference in strength between the two yarns – for all materials – can be attributed to the “composite” nature of the insulated yarn and the resulting differences in the response to tensile deformation.

4.1.2 Characterization of Conductive Yarns Woven into Fabric

4.1.2.1 Testing Variables Specification

The next step has been to characterize fabrics containing conductive yarns. Therefore, the yarns listed in Figure 14 have been woven into a set of fabrics, which have then been used in a series of experiments to test the effects of:

- conductive yarn material type (all yarns with and without insulation);
- signal frequency (210 Hz to 1010 Hz);
- applied voltage (1.3 V to 1.9 V);
- type of deformation (Constant Rate of Loading, Constant Rate of Elongation); and
- tensile strain rate (0 % to breaking strain)

on the electrical and tensile properties of fabrics used in E-textiles.

4.1.2.2 Test Methods

The same test methods used earlier for yarns (section 4.1.1.1) were used to test the conductive yarns woven into fabrics.

4.1.2.3 Testing Sample Characteristics

- Sample Size: 300mm X 15 mm
- Fabric Composition
  - Material
    - Warp: 18s 100% Cotton,
    - Weft: 30s core-spun spandex for base and conductive yarn listed in Figure 14.
  - Structure
    - Plain Weave
    - Ends/inch: 24
    - Picks/inch: 24 (Base) + 1 (Conductive Yarn)

4.1.2.4 Testing Set-up for Electrical Properties

The same testing set-up used earlier for yarns (section 4.1.1.2) was used for testing the fabrics.

4.1.2.5 Results and Discussion: Electrical Properties of Conductive Yarn Woven into Fabric

Table 3 shows the summary of results of the range of tests on the fabric samples (see Figure 14 for explanation of material types). The values represent the average of three test specimens per sample (see ASTM D-2256 for details).

Table 3. Summary of Test Results

Material	Resistance at 0%	Resistance at Break[5,6]	Breaking Tensile Strain	Breaking Load
	Ohm	Ohm	%	Kgf
A1	20.66	21.18	14.54	2.34
A2	20.57	20.92	17.01	0.53
B1	0.22	0.23	11.33	1.66
B2	0.28	0.30	24.9	4.27
C1	0.77	0.91	4.0	6.15
C2	1.28	1.44	20.0	4.76
D1	88.61	469.01	29.8	3.23
D2	60.96	507.9	48.09	3.25

[5] The resistance of the material is calculated using Ohm's Law and the set of equations (Figure 17):

$V_1=I*(R+Y)$
$V_2=I*Y$
$V_1 / V_2 = I * (R+Y) / I * Y$

Therefore, $Y = RV_2 / (V_1-V_2)$

Where
V_1: The voltage from Function Generator,
V_2: The voltage measure on the Multimeter,
R: The external resistor,
Y: The resistance of the yarn,
I: The current in the circuit.

[6] The value of Resistance at Break of each material is measured at 1010 Hz and 1.9v.

Stainless Steel (Material A)

Effect of Tensile Strain on Insulated Yarn in Woven Fabric

- There is no significant effect of tensile strain on the resistance of insulated stainless steel yarn woven into the fabric when the strain is increased from 0% to 10% but the resistance increases by 33% at 12% tensile strain as shown in Table 4 and Figure 44.

Table 4. Resistance of Insulated Stainless Steel Yarn in Woven Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	20.66	20.66	20.66	20.66
0.5 %	20.63	20.63	20.63	20.63
1 %	20.62	20.62	20.62	20.62
1.5 %	20.60	20.61	20.61	20.61
3 %	20.59	20.60	20.59	20.60
5 %	20.59	20.59	20.59	20.59
10 %	22.04	22.04	22.04	22.02
12 %	27.55	27.53	27.54	27.56

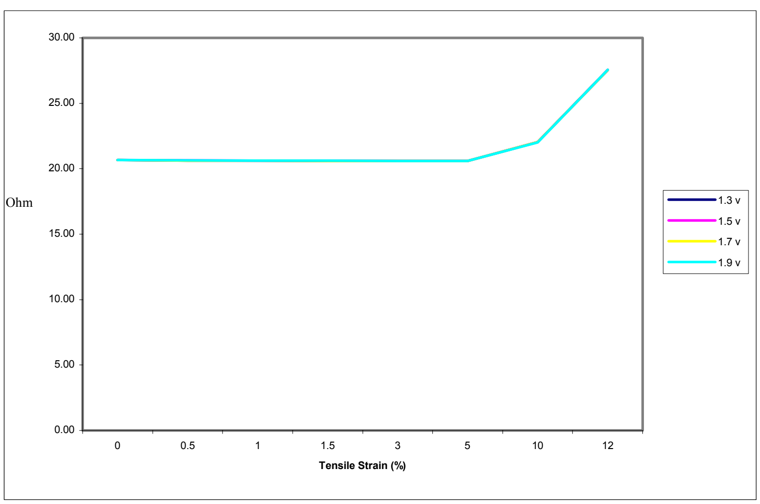


Figure 44. Resistance of Insulated Stainless Steel Yarn in Woven Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of the insulated stainless steel yarn woven into the fabric (Table 5 and Figure 45).

Table 5. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**0.5 %**	**1 %**	**1.5 %**	**3 %**	**5 %**	**10 %**	**12 %**
210 Hz	20.69	20.64	20.63	20.61	20.60	20.59	22.00	27.60
410 Hz	20.68	20.64	20.63	20.61	20.60	20.60	21.99	27.40
610 Hz	20.67	20.64	20.62	20.61	20.60	20.59	21.98	27.58
810 Hz	20.67	20.64	20.62	20.61	20.60	20.59	22.03	27.67
1010 Hz	20.66	20.63	20.62	20.61	20.60	20.59	22.02	27.56

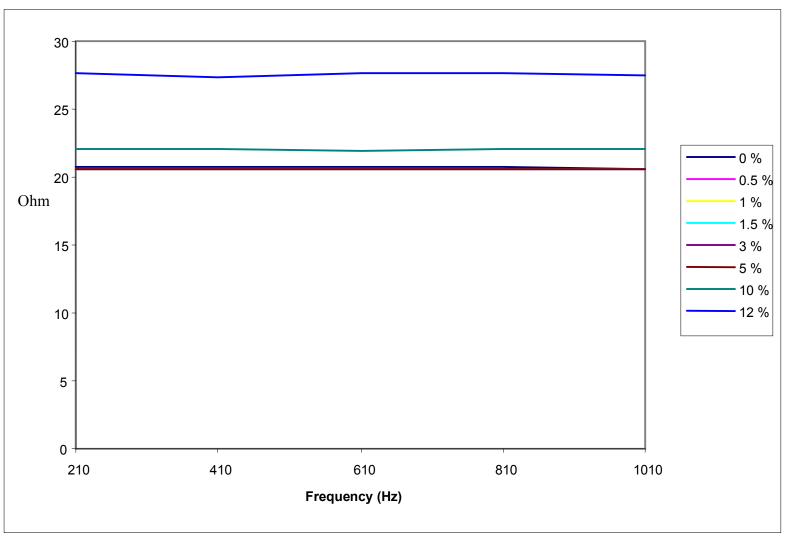


Figure 45. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strain

- At any given tensile strain, there is also no significant effect of voltage on the resistance of an insulated stainless steel yarn woven into the fabric. (Table 6 & Figure 46)

Table 6. Resistance of Insulated Stainless Steel Yarn woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**0.5 %**	**1 %**	**1.5 %**	**3 %**	**5 %**	**10 %**	**12 %**
1.3 v	20.66	20.63	20.62	20.60	20.59	20.59	22.04	27.55
1.5 v	20.66	20.63	20.62	20.61	20.60	20.59	22.04	27.53
1.7 v	20.66	20.63	20.62	20.61	20.59	20.59	22.04	27.54
1.9 v	20.66	20.63	20.62	20.61	20.60	20.59	22.02	27.56

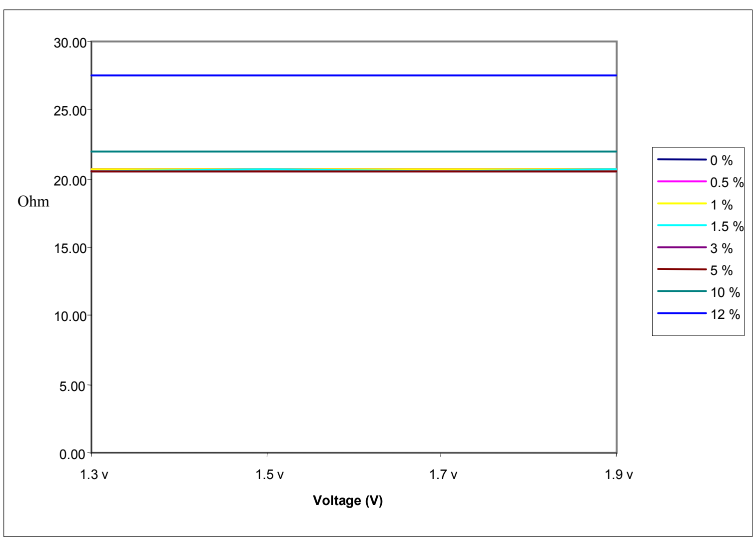


Figure 46. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Effect of Tensile Strain on Uninsulated Yarn in Woven Fabric

- There is no significant effect of tensile strain on the resistance of uninsulated stainless steel yarn woven into a fabric when the strain increases from 0% to 10%. But the resistance of this yarn increases by 33.87% at 15% strain as shown in Table 7 and Figure 47. This is because the yarn starts to break at around 10% strain although the breaking tensile strain of this material is 17.01%.

Table 7. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	20.58	20.57	20.58	20.57
0.5 %	20.68	20.69	20.69	20.68
1 %	20.72	20.73	20.73	20.73
1.5 %	20.74	20.75	20.75	20.75
3 %	20.61	20.62	20.62	20.62
5 %	20.61	20.62	20.62	20.63
10 %	20.92	20.92	20.92	20.92
15 %	27.55	27.53	27.54	27.56

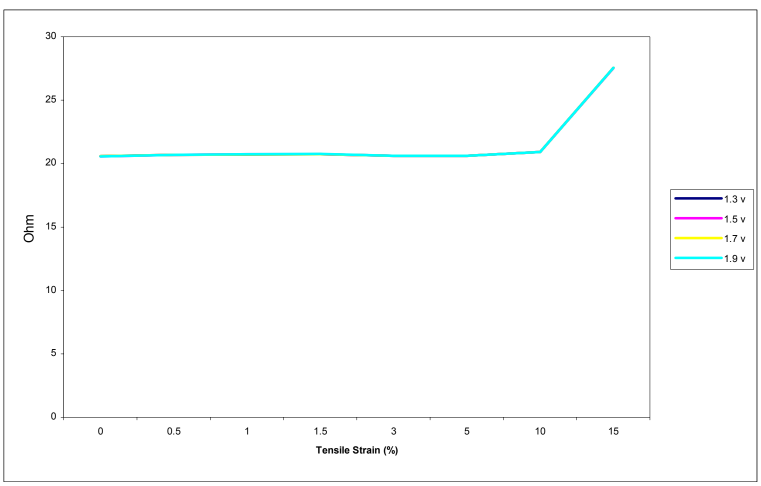


Figure 47. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Tensile Strains and Voltages

- There is no significant effect of frequency on the resistance of an uninsulated stainless steel yarn woven into the fabric as the tensile strain increases from 0% to 10%. The resistance, however, increases differently at different frequencies at 15% tensile strain. Especially, the resistance increases from 20.73 ohm to 103.71 ohm, which is an increase of 400% at 610 Hz, but at 1010 Hz increases only by 34%. This is because the conductive yarn starts to break inside the fabric from around 10%. Therefore, the conductivity at 15% is not from the whole strand of fibers, rather it is from only a few of the unbroken ones (Table 8 & Figure 48).

Table 8. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**0.5 %**	**1 %**	**1.5 %**	**3 %**	**5 %**	**10 %**	**15 %**
210 Hz	20.72	20.66	20.74	20.75	20.60	20.59	20.97	44.40
410 Hz	20.81	20.73	20.74	20.75	20.61	20.57	20.87	93.27
610 Hz	20.73	20.70	20.73	20.75	20.60	20.58	20.91	103.71
810 Hz	20.69	20.70	20.73	20.74	20.61	20.59	20.93	27.67
1010 Hz	20.57	20.68	20.73	20.75	20.62	20.63	20.92	27.56

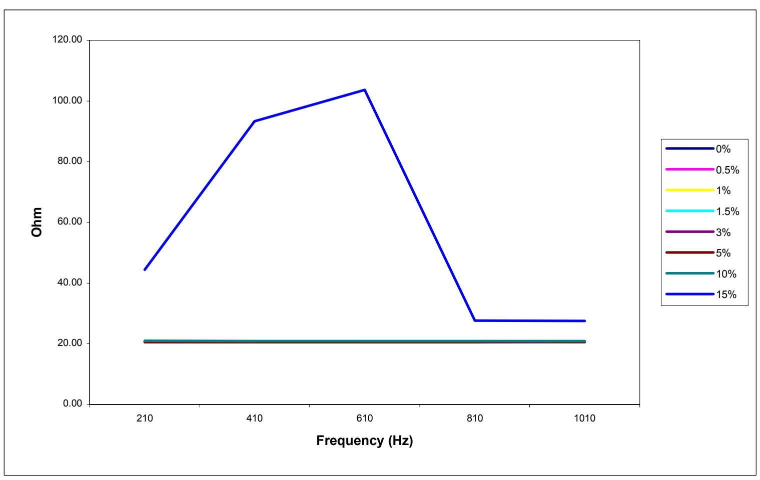


Figure 48. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant effect of applied voltage on the resistance of an uninsulated stainless steel yarn woven into fabric (Table 9 & Figure 49).

Table 9. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**0.5 %**	**1 %**	**1.5 %**	**3 %**	**5 %**	**10 %**	**15 %**
1.3 v	20.58	20.68	20.72	20.74	20.61	20.61	20.92	27.55
1.5 v	20.57	20.69	20.73	20.75	20.62	20.62	20.92	27.53
1.7 v	20.58	20.69	20.73	20.75	20.62	20.62	20.92	27.54
1.9 v	20.57	20.68	20.73	20.75	20.63	20.63	20.92	27.56

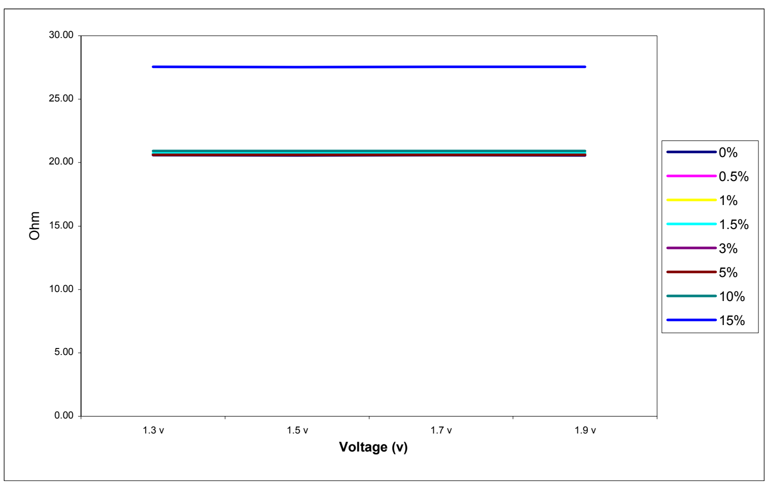


Figure 49. Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Copper (Material B)

Effect of Tensile Strain on Insulated Yarn in Woven Fabric

- There is no significant effect of tensile strain on the resistance of insulated copper yarn woven in fabric when the strain is increased from 0% to 8% as shown in Table 10 and Figure 50. The tensile breaking strain of this yarn is 11.33%.

Table 10. Resistance of Insulated Copper Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	0.22	0.22	0.22	0.22
5 %	0.23	0.23	0.23	0.23
8 %	0.23	0.23	0.23	0.23

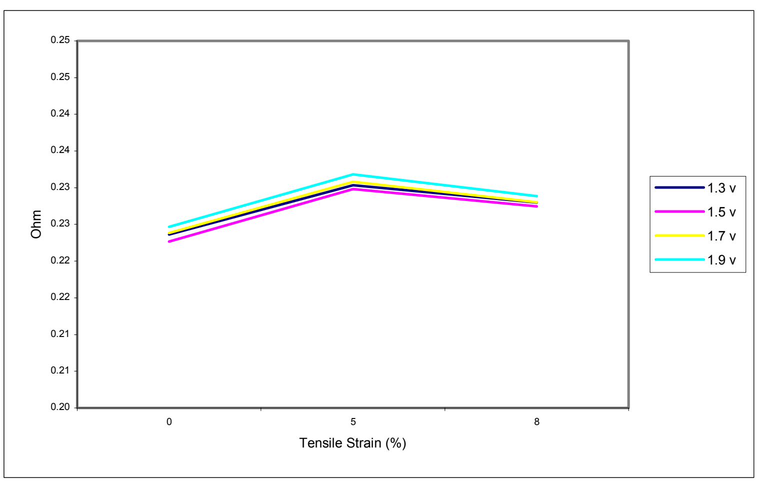


Figure 50. Resistance of Insulated Copper Yarn Woven into Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of an insulated copper yarn woven into fabric (Table 11 & Figure 51).

Table 11. Resistance of Insulated Copper Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**5 %**	**8 %**
210 Hz	0.24	0.23	0.23
410 Hz	0.22	0.23	0.23
610 Hz	0.22	0.23	0.23
810 Hz	0.22	0.23	0.23
1010 Hz	0.22	0.23	0.23

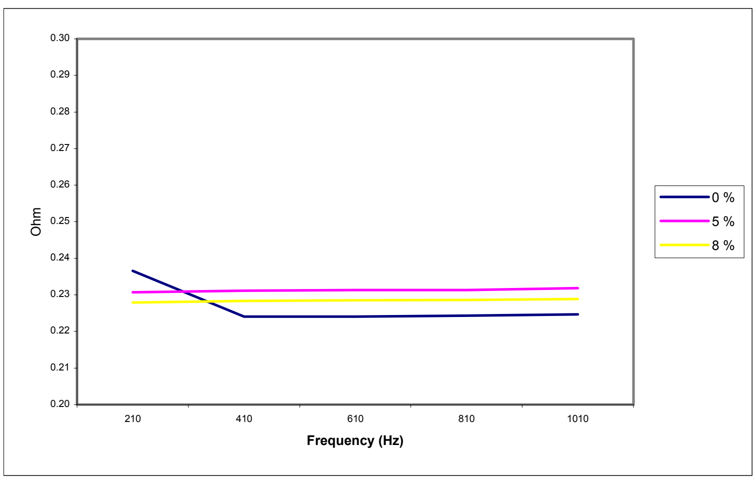


Figure 51. Resistance of Insulated Copper Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant effect of applied voltages on the resistance of an insulated copper yarn woven into fabric (Table 12 & Figure 52).

Table 12. Resistance of Insulated Copper Yarn Woven into the Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**3 %**	**8 %**
1.3 v	0.22	0.23	0.23
1.5 v	0.22	0.23	0.23
1.7 v	0.22	0.23	0.23
1.9 v	0.22	0.23	0.23

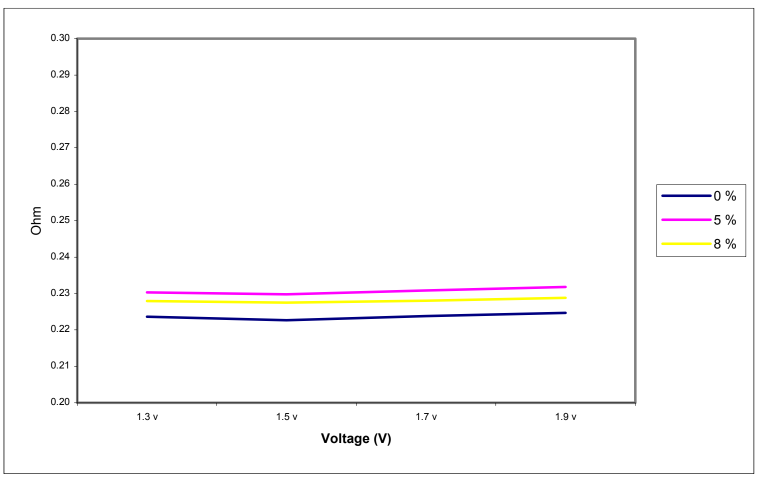


Figure 52. Resistance of Insulated Copper Yarn Woven into the Fabric at different Applied Voltages and Tensile Strains

Effect of Tensile Strain on Uninsulated Yarn in Woven Fabric

- There is no significant effect of tensile strain on the resistance of uninsulated copper yarn woven into fabric when the strain is increased from 0% to 20% (Table 13 and Figure 53). The average breaking tensile strain of this yarn is 24.9%.

Table 13. Resistance of Uninsulated Copper Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	0.28	0.28	0.28	0.28
5 %	0.29	0.29	0.29	0.29
10 %	0.29	0.29	0.30	0.30
15 %	0.30	0.30	0.30	0.30
20 %	0.30	0.30	0.30	0.30

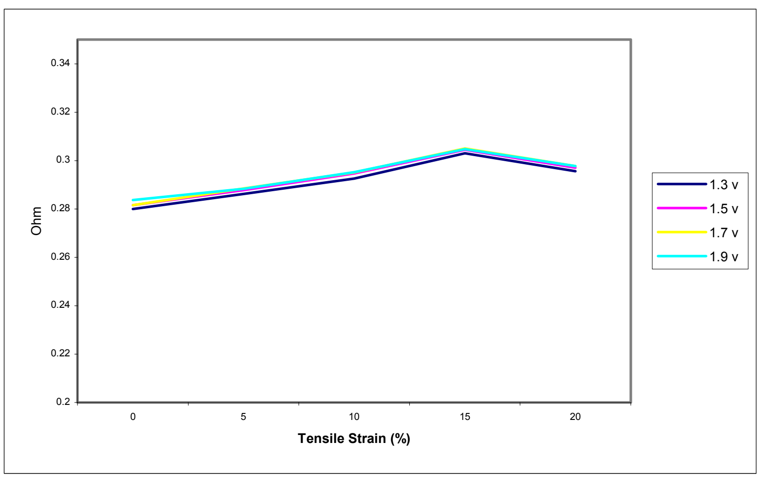


Figure 53. Resistance of Uninsulated Copper Yarn Woven into Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of uninsulated copper yarn woven into fabric as shown in Table14 and Figure 54.

Table 14. Resistance of Uninsulated Copper Yarn Woven into Fabric at different Frequencies

Unit: ohm

	0 %	**5 %**	**10 %**	**15 %**	**20 %**
210 Hz	0.26	0.29	0.30	0.30	0.30
410 Hz	0.26	0.29	0.30	0.30	0.30
610 Hz	0.26	0.29	0.29	0.30	0.30
810 Hz	0.26	0.29	0.29	0.30	0.30
1010 Hz	0.28	0.29	0.30	0.30	0.30

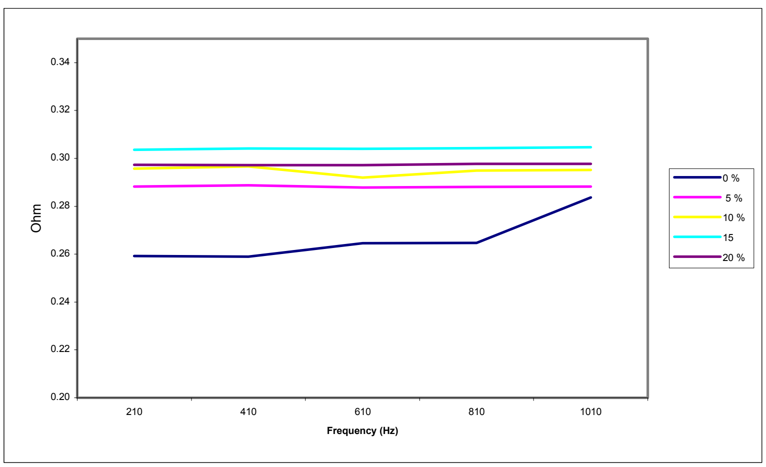


Figure 54. Resistance of Uninsulated Copper Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant change in resistance of the conductive yarn woven into the fabric at different voltages (Table 15 and Figure 55).

Table 15. Resistance of Uninsulated Copper Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**5 %**	**10 %**	**15 %**	**20 %**
1.3 v	0.28	0.29	0.29	0.30	0.30
1.5 v	0.28	0.29	0.29	0.30	0.30
1.7 v	0.28	0.29	0.30	0.30	0.30
1.9 v	0.28	0.29	0.30	0.30	0.30

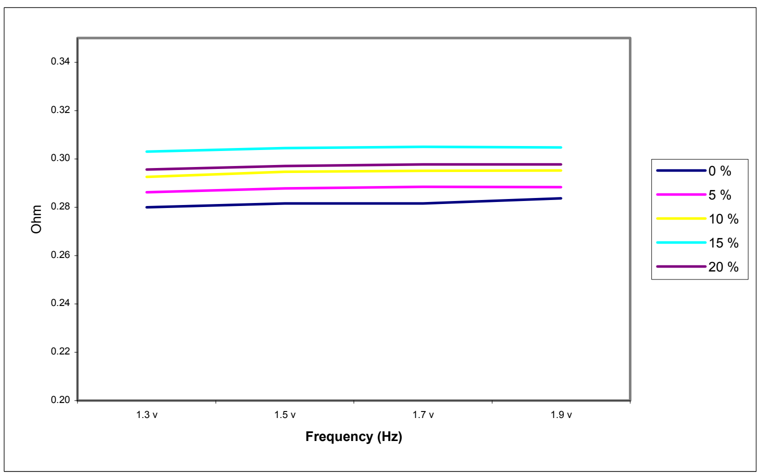


Figure 55. Resistance of Uninsulated Copper Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Metal-Clad Aramid (Material C)

<u>Effect of Tensile Strain on Insulated Yarn in Woven Fabric</u>

- There is no significant effect of tensile strain on the resistance of insulated Metal-Clad Aramid yarn woven into fabric when the strain is increased from 0% to 2% at different voltages. However, the resistance of the yarn starts to increase by 16.7% from 2% to 3% as shown in Table 16 and Figure 56. The breaking tensile strain of this yarn is 4.0%.

Table 16. Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	0.78	0.77	0.77	0.77
1 %	0.77	0.77	0.77	0.77
2 %	0.78	0.78	0.78	0.78
3 %	0.91	0.91	0.91	0.91

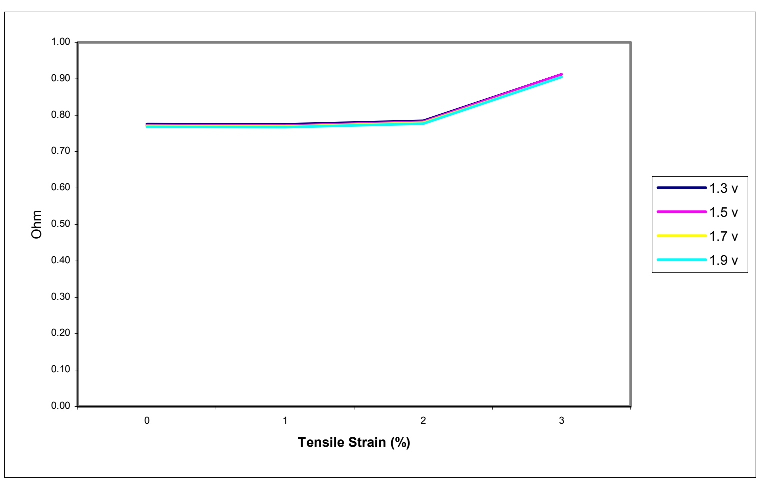


Figure 56. Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of insulated Metal-Clad Aramid yarn woven into fabric (Table 17 and Figure 57).

Table 17. Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**1 %**	**2 %**	**3 %**
210 Hz	0.77	0.77	0.78	0.90
410 Hz	0.77	0.77	0.78	0.90
610 Hz	0.77	0.77	0.78	0.91
810 Hz	0.77	0.77	0.78	0.91
1010 Hz	0.77	0.77	0.78	0.91

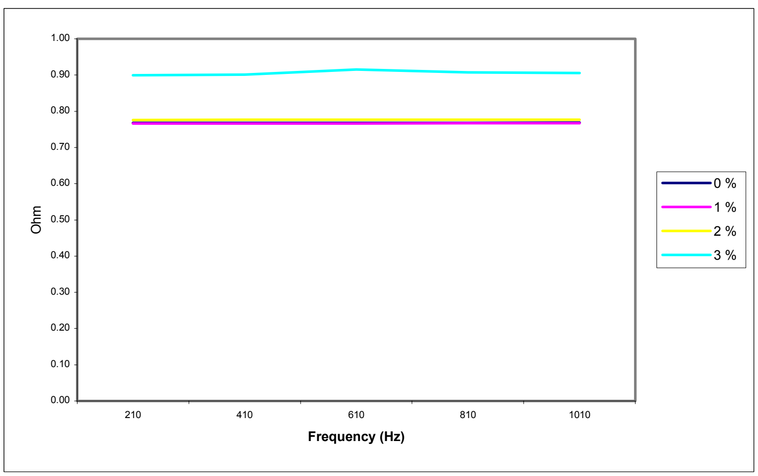


Figure 57. Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant effect of voltage on the resistance of insulated Metal-Clad Aramid yarn woven into fabric (Table 18 and Figure 58).

Table 18. Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**1 %**	**2 %**	**3 %**
1.3 v	0.78	0.77	0.78	0.91
1.5 v	0.77	0.77	0.78	0.91
1.7 v	0.77	0.77	0.78	0.91
1.9 v	0.77	0.77	0.78	0.91

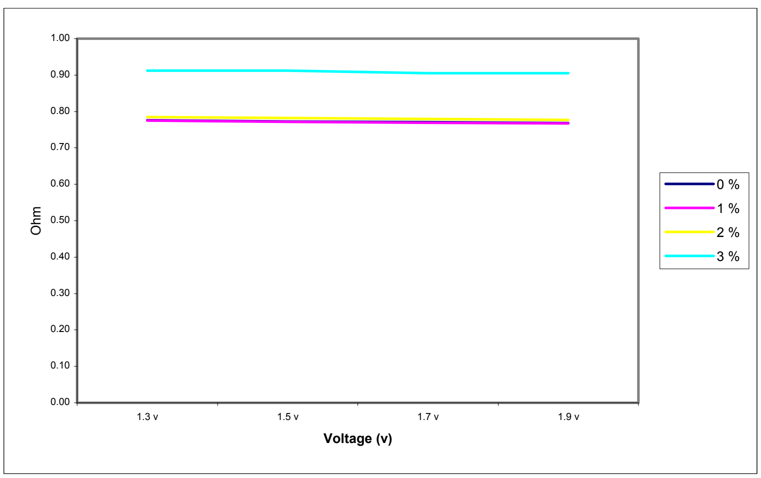


Figure 58. Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Effect of Tensile Strain on Uninsulated Yarn in Woven Fabric

- There is no significant effect of tensile strain on the resistance of uninsulated Metal-Clad Aramid yarn woven into fabric when the strain is increased from 0% to 5% at different voltages. The resistance of the yarn gradually increases by 7% when the tensile strain is increased from 5% to 10%, and by 5% when the strain increases from 10% to 15%. The overall increase in resistance of the yarn is 12.5% from 0% to 15% as shown in Table 19 and Figure 59. The breaking tensile strain of this yarn is 20%.

Table 19. Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	1.28	1.27	1.28	1.28
2 %	1.28	1.28	1.28	1.28
5 %	1.28	1.28	1.28	1.28
10 %	1.37	1.37	1.37	1.37
15 %	1.44	1.44	1.44	1.44

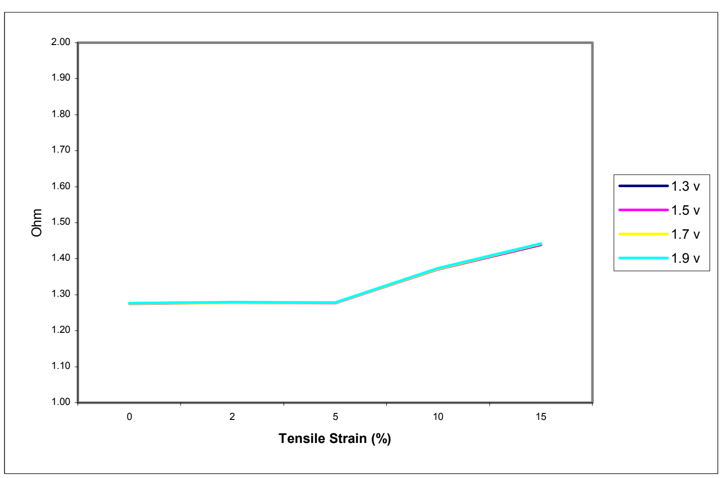


Figure 59. Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of uninsulated Metal-Clad Aramid yarn woven into fabric (Table 20 and Figure 60).

Table 20. Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**2 %**	**5 %**	**10 %**	**15 %**
210 Hz	1.28	1.28	1.28	1.37	1.44
410 Hz	1.28	1.28	1.28	1.37	1.44
610 Hz	1.28	1.28	1.28	1.37	1.44
810 Hz	1.28	1.28	1.28	1.37	1.44
1010 Hz	1.28	1.28	1.28	1.37	1.44

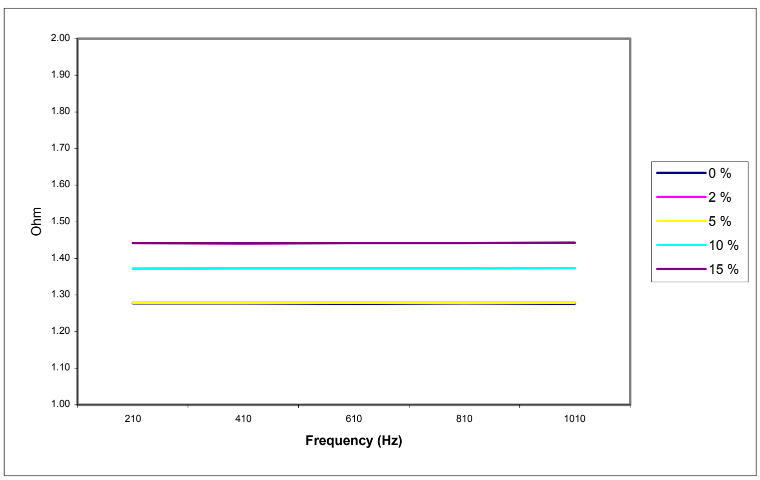


Figure 60. Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant effect of voltage on the resistance of uninsulated Metal-Clad Aramid yarn woven into fabric (Table 21 and Figure 61).

Table 21. Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**2 %**	**5 %**	**10 %**	**15 %**
1.3 v	1.28	1.28	1.28	1.37	1.44
1.5 v	1.27	1.28	1.28	1.37	1.44
1.7 v	1.28	1.28	1.28	1.37	1.44
1.9 v	1.28	1.28	1.28	1.37	1.44

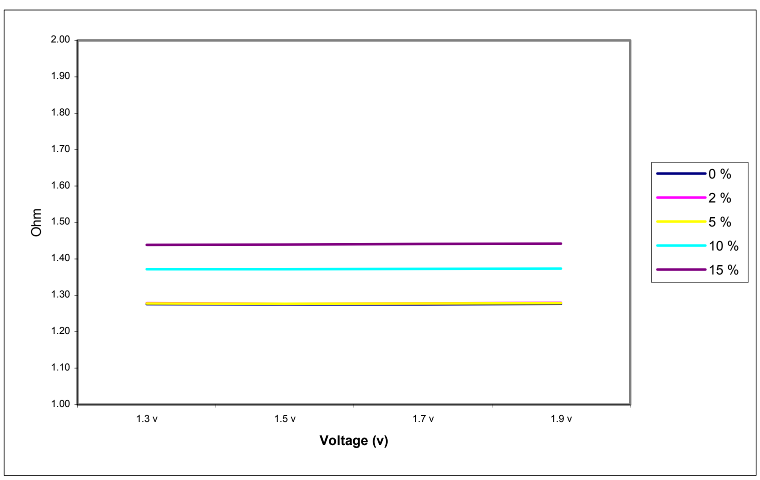


Figure 61. Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Nylon Doped with Silver (Material D)

Effect of Tensile Strain on Insulated Yarn in Woven Fabric

- There is a significant effect of tensile strain on the resistance of insulated Nylon doped with silver yarn woven into fabric when the strain increases from 0% to 25% at different voltages (breaking tensile strain is 29.8%). As shown in Table 22 and Figure 62, the resistance is approximately 88-89 ohm at 0% and 5% tensile strains. It then increases gradually to 470 Ohm at 25% – a significant increase of 435%. Unlike the case of other materials, this increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain, depending on processing conditions).

Table 22. Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	88.95	88.57	88.59	88.61
5 %	89.19	89.17	89.18	89.20
10 %	122.57	122.62	122.56	122.62
15 %	202.00	202.01	202.02	202.00
20 %	302.82	302.88	302.91	302.94
25 %	467.81	467.95	467.77	468.01

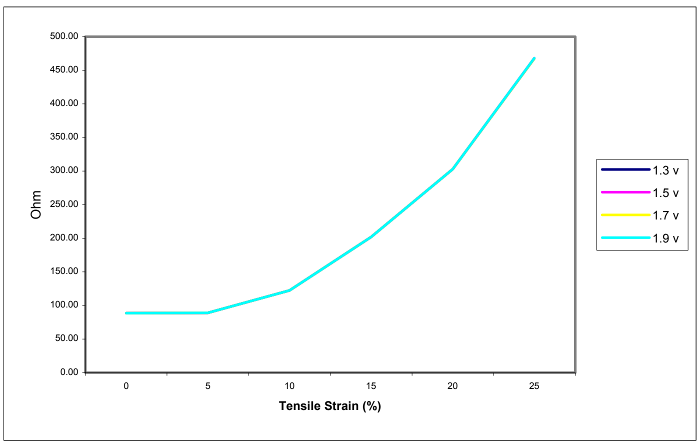


Figure 62. Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of insulated Nylon doped with silver yarns woven into fabric (Table 23 and Figure 63).

Table 23. Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25 %**
210 Hz	83.22	89.24	122.78	202.84	304.56	470.79
410 Hz	88.67	89.23	122.73	202.59	304.01	469.77
610 Hz	88.64	89.21	122.68	202.34	303.59	469.01
810 Hz	88.62	89.21	122.64	202.16	303.24	468.61
1010 Hz	88.61	89.20	122.62	202.00	302.94	468.01

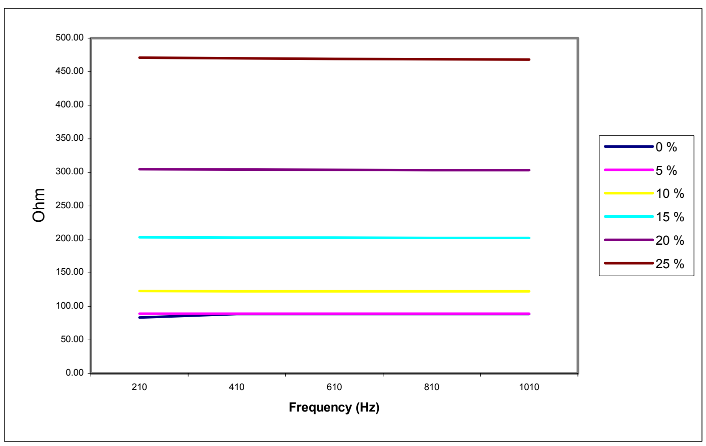


Figure 63. Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant effect of voltage on the resistance of insulated Nylon doped with silver yarns (Table 24 and Figure 64).

Table 24. Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25 %**
1.3 v	88.59	89.19	122.57	202.00	302.82	47.81
1.5 v	88.57	89.17	122.62	202.01	302.88	467.95
1.7 v	88.59	89.18	122.56	202.02	302.91	467.77
1.9 v	88.61	89.20	122.62	202.00	302.94	468.01

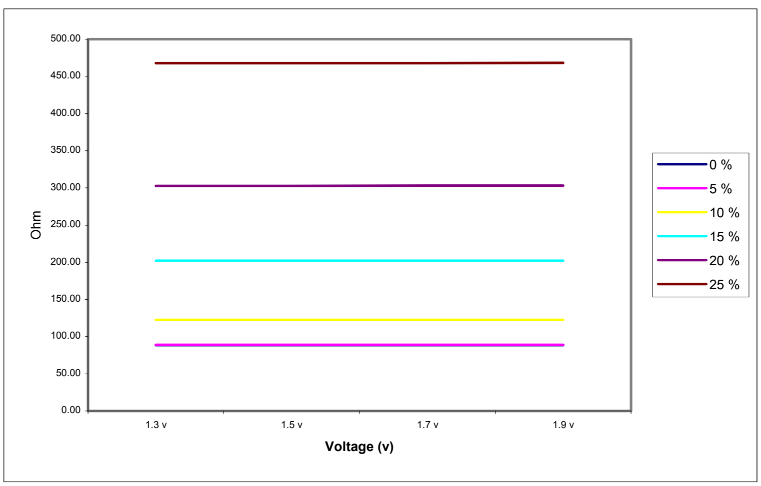


Figure 64. Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Effect of Tensile Strain on Uninsulated Yarn in Woven Fabric

- There is no significant effect of tensile strain on the resistance of uninsulated Nylon doped with silver yarn woven into fabric when the tensile strain is increased from 0% to 10% at different voltages. The resistance starts to increase from 61 Ohm at 0% strain to 66 Ohm at 15% tensile strain – an increase of 8%. It then increases gradually, but at a higher rate, to 506 Ohm at 40% (breaking strain is 48.09%) – a remarkable increase of 730% (Table 25 and Figure 65). This increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain), depending on processing conditions.

Table 25. Resistance of Uninsulated Nylon Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 v	**1.5 v**	**1.7 v**	**1.9 v**
0 %	60.93	60.96	60.96	60.96
5 %	60.86	60.88	60.86	60.82
10 %	61.74	61.76	61.75	61.73
15 %	66.19	66.22	66.17	66.16
20 %	92.14	92.10	92.17	92.23
25 %	144.26	144.29	144.29	144.27
30 %	212.99	212.96	212.95	212.89
35 %	329.54	329.61	329.49	329.54
40 %	506.32	506.61	505.97	506.01

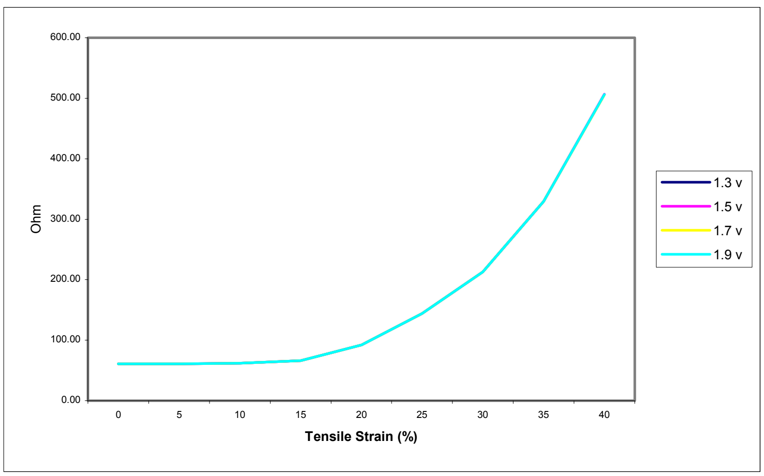


Figure 65. Resistance of Uninsulated Nylon Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

- At any given tensile strain, there is no significant effect of frequency on the resistance of insulated Nylon doped with silver yarn woven into fabric (Table 26 and Figure 66).

Table 26. Resistance of Uninsulated Nylon Doped with Silver Yarn woven in fabric at different Frequencies and Tensile Strains

Unit: ohm

	0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25 %**	**30 %**	**35 %**	**40 %**
210 Hz	60.80	61.03	61.77	66.18	92.61	145.06	214.11	331.51	508.88
410 Hz	60.80	60.95	61.71	66.34	92.68	144.63	213.73	330.98	507.30
610 Hz	60.86	60.96	61.72	66.26	92.32	144.43	213.32	330.45	507.06
810 Hz	60.85	60.91	61.74	66.19	92.07	144.24	212.99	330.04	506.58
1010 Hz	60.96	60.82	61.73	66.16	92.23	144.27	212.89	324.54	506.01

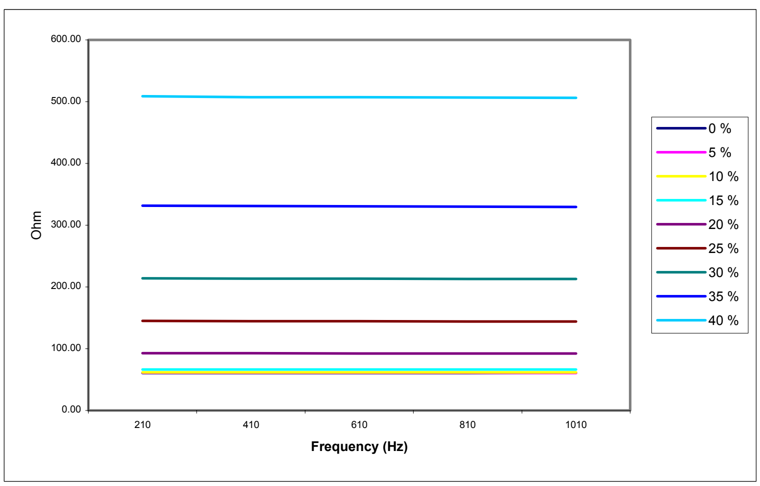


Figure 66. Resistance of Uninsulated Nylon Doped with Silver Yarn Woven into Fabric at different Frequencies and Tensile Strains

- At any given tensile strain, there is no significant effect of voltage on the resistance of insulated Nylon doped with silver yarn woven into fabric (Table 27 and Figure 67).

Table 27. Resistance of Uninsulated Nylon Doped with Silver Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

Unit: ohm

	0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25 %**	**30 %**	**35 %**	**40 %**
1.3 v	60.93	60.86	61.74	66.19	92.14	144.26	212.99	329.54	506.32
1.5 v	60.96	60.88	61.76	66.22	92.10	144.29	212.96	329.61	506.61
1.7 v	60.96	60.86	61.75	66.17	92.17	144.29	212.95	329.49	505.97
1.9 v	60.96	60.82	51.73	66.16	92.23	144.27	212.89	329.54	506.01

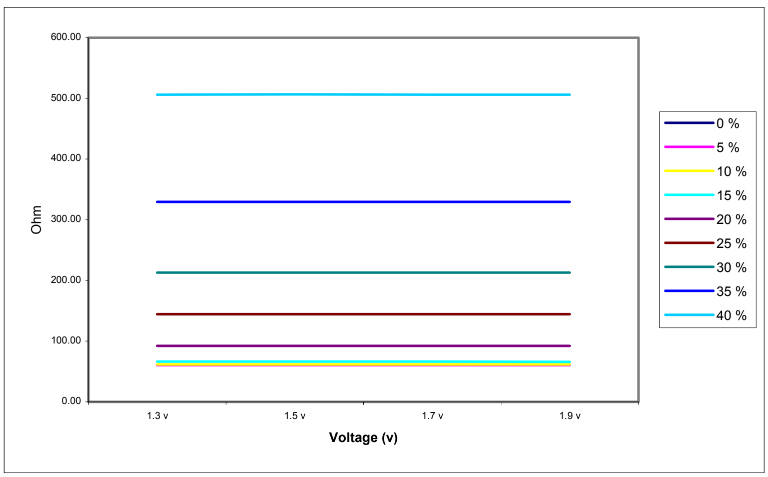


Figure 67. Resistance of Uninsulated Nylon Doped with Silver Yarn Woven into Fabric at different Applied Voltages and Tensile Strains

4.1.2.6 Summary of Electrical Properties of Conductive Yarn Woven into Fabrics

Table 28 shows a diagrammatic representation of the effects of tensile strain, frequency and voltage on the electrical resistance of insulated and uninsulated conductive yarns woven into fabrics for E-Textiles.

Table 28. Diagrammatic Representation of Electrical Properties of Materials in Fabrics

Material Type		Strain	Frequency	Voltage
Stainless Steel	Insulated	↑	↔	↔
	Uninsulated	↑	↔	↔
Copper	Insulated	↔	↔	↔
	Uninsulated	↔	↔	↔
Metal Clad Aramid	Insulated	↑	↔	↔
	Uninsulated	↑	↔	↔
Nylon doped with Silver	Insulated	↑↑	↔	↔
	Uninsulated	↑↑	↔	↔

<u>Notation:</u>

↔	↑	↑↑
No Change	Increase	Significant Increase

Effect of Tensile Strain on Conductive Yarn Woven into Fabric

As shown in Table 28, the resistance of different conductive yarns woven into fabric (except Copper yarn) increases with increases in tensile strain. However, the variation of electrical resistance of the yarns starts to increase when the tensile strain of the yarn is close to its breaking strain. There is no effect of tensile strain on the conductive yarns during the initial stages of tensile strain. Unlike the other conductive yarns, the Nylon doped with silver yarn stretches right from the beginning of tensile strain. This is because Nylon is highly extensible, (25%-30% breaking strain) and this conductive yarn begins to stretch as soon as the base fabric is subjected to stretch. In other cases, the base fabric stretches before the conductive yarn in the woven fabric because the base fabric has higher elongation than the conductive yarn.

Effect of Frequency and Applied Voltage on Conductive Yarn Woven into Fabric

As shown in Table 28, there is no significant effect of frequency and voltage on all tested conductive yarns woven into fabric at any given tensile strain. This behavior is similar to that of the conductive yarns tested in yarn form.

Thus, this facet of the research has resulted in a better understanding of the characteristics of conductive materials – in yarn and yarn-in-fabric forms – for use in E-Textiles.

4.2 Textillography: A Novel Technology for Interconnection Architecture in E-Textiles

One of the key requirements for realizing the vision of E-textiles is the design and incorporation of physical data paths i.e., the realization of “textile electrical circuits.” A robust and cost-effective *interconnection technology* is critical for engineering the desired circuits in the fabric. Past research on manual interconnection technology utilized in the Wearable Motherboard and the research during the early phases of this project exploring the use of “insulation displacement conductors” pointed out the need for an automated, “scalable” interconnection technology to facilitate the production of E-textiles on a much larger scale (quantity) and dimensions (large surface areas). An enabling technology is essential for realizing E-Textiles. Therefore, a conceptual framework for such a technology has been developed. It has been named *Textillography*. Just as stereolithography has revolutionized the design and development of 3-D parts, it is hoped that Textillography will lead to the rapid realization of interconnection architectures in textile structures.

There are two modes in which the proposed technology can be applied to the fabric: on the loom or off the loom, each with its own set of advantages. For instance, the fabric’s topology is defined and better controlled when it is being produced, making a case for on-loom textillography. On the other hand, the fabric production process might be adversely affected by the interconnection process (e.g., slowing down of the production rate). Thus, the proposed concept of Textillography opens up an interesting avenue of research.

4.2.1 The Conceptual Framework for Off-Loom Textillography

Figure 68 shows the proposed set-up and sequence of operations for the “off-loom” Textillography process. In Step 1, the solvent is applied at the “desired” interconnection points using the Mesh (with dispensers) that is placed on the fabric. In Step 2, the interconnection points are “excited” using an ultrasonic device to establish the desired contact between the fibers/yarns in the fabric. The Anvil profile is also shown in the figure and it resembles the yarn intersection. In the final step, Step 3, a conductive epoxy is used to bond and firmly establish the interconnection. The interconnections can be accomplished through chemical bonding, laser etching and bonding, and ultrasonic welding. By building the system around a “turn table” type configuration, multiple pieces of fabric can be processed in sequence resulting in an “assembly line” process to facilitate processing of longer and wider lengths of fabric.

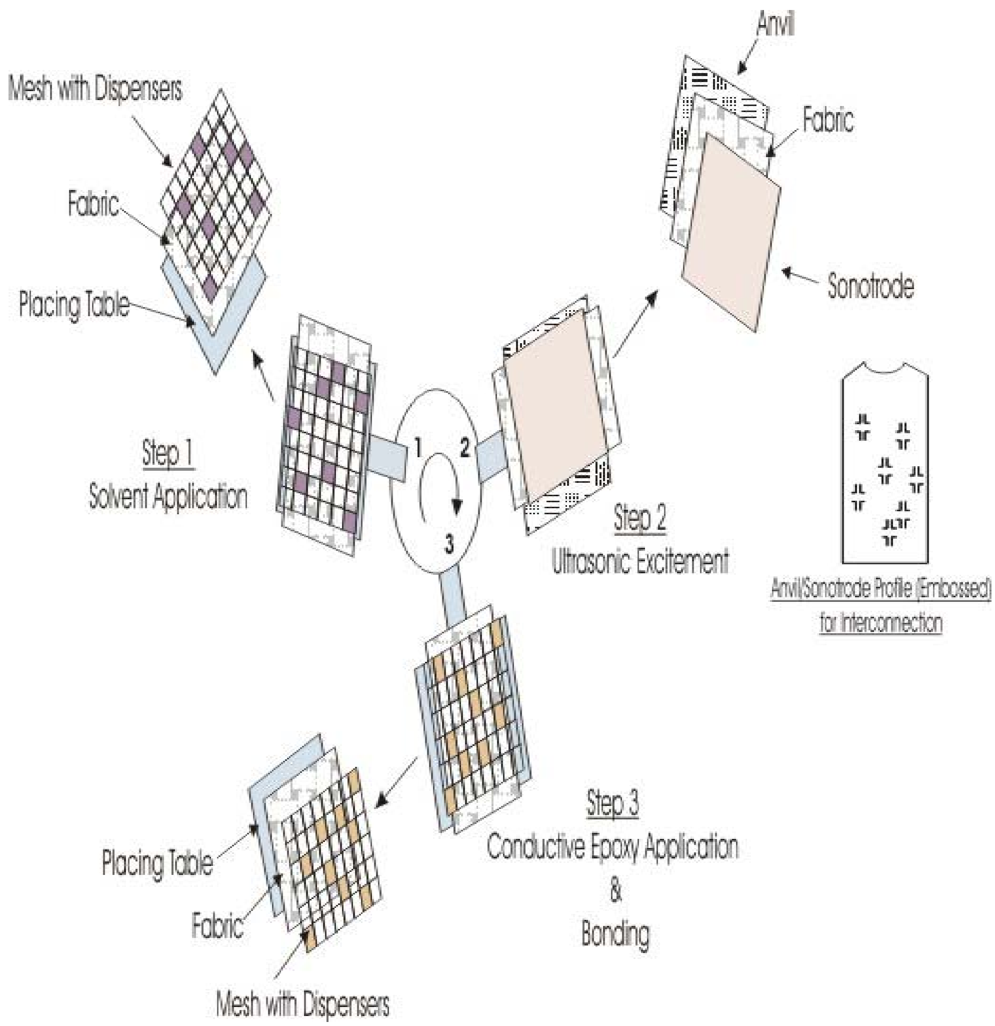


Figure 68. Schematic of Off-Loom Textillography

4.2.2 The Conceptual Framework for On-Loom Textillography

Figure 69 shows the proposed set-up and sequence of operations for the on-loom Textillography system. The Textillography device – mounted on a rail – will be positioned in real-time at the desired warp/filling interconnection after the fabric has been formed (after the beater as shown in the figure). In Step 1, the Dispenser containing the solvent moves to the desired interconnection point to dispense the solvent. In Step 2, the Sonotrode (with a yarn intersection profile) moves into place to excite the junction. Finally, the conductive epoxy is applied in Step 3. While the illustration is for ultrasonic process, a similar process will work for chemical bonding and laser-etching and bonding as well. Thus, the proposed "on-loom" Textillography will lead to the realization of interconnection architectures in real-time and in desired configurations.

In short, the proposed "Textillography" technology can facilitate the production of E-Textiles with desired performance capabilities, potentially during the manufacturing process itself.

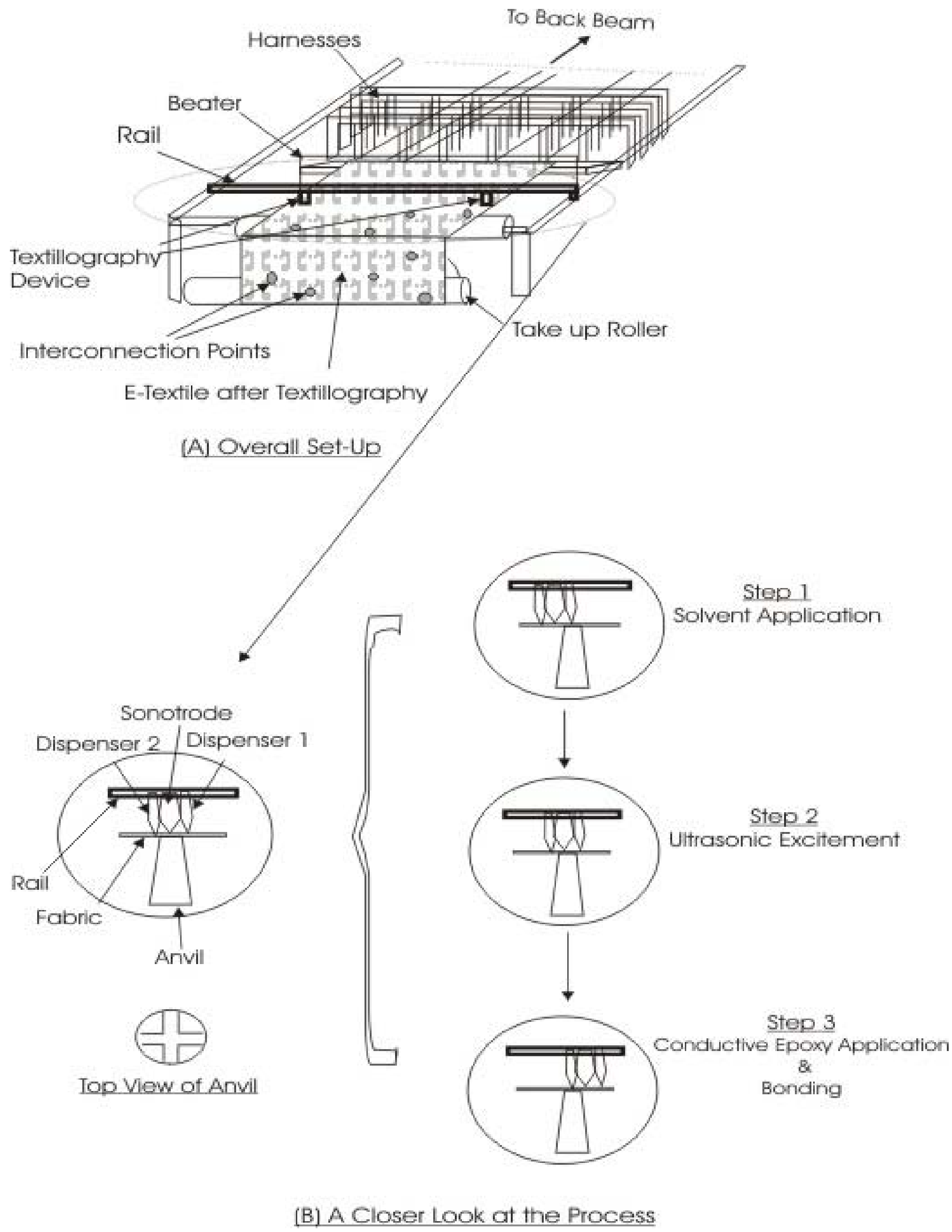


Figure 69. Schematic of On-Loom Textillography

5. A PARADIGM SHIFT: FROM E-TEXTILES TO *i*-TEXTILES

The term "E-Textiles" is being used in the field to typically denote the class of structures that integrates electronics elements with textiles. However, the term "E-Textiles" doesn't convey the "interactivity" that is key to the successful development and deployment of such structures. Therefore, we propose the term "*i*-Textiles" or *interactive* textiles to convey this "dynamic" or "interactive" nature of structures that goes beyond just the integration of "electronic" elements into textile structures. It is not just the substitution of the word "interactive" for "electronics", rather it is a paradigm shift with regards to these structures that calls for going beyond the simple incorporation of electronic devices on to the fabric – the fabric does indeed become the computer eventually, making it a truly *adaptive and responsive textile structure*. The user-fabric symbiosis and dynamics open up new frontiers in textiles and human factors research. Although it would require extensive research and development to realize this paradigm in its entirety, it is important to adopt this long-term view and develop the "building blocks" (see Figure 13) that are critical to this vision. The work on two of the building blocks – Platform and Interconnection Architecture – discussed in Section 4 lays the foundation for this class of "adaptive and responsive textile structures" or "*i*-Textiles."

5.1 Performance Characteristics of *i*-Textiles

The important performance characteristics required of *i*-Textiles are shown in Table 29. The *functionality* requirement is that the resulting structure serves as a "flexible motherboard" and the specific domain of application will define additional functionality requirements. The set of factors related to the usage of the product are captured under *usability*, while others related to *durability*, *manufacturability*, and so on, are similarly grouped, as shown in the table. Of course, the end-use application of the product will determine the *relative* importance of the characteristics shown in the table and the specific values of the parameters. In addition to the "generic" performance characteristics, there will be a set of "application-specific" requirements that must be considered in the design and development of the product depending on the application field, viz., battlefield, medicine, firefighting, etc.

Table 29. Performance Characteristics of *i*-Textiles

Functionality	• Act as a Textile Elastic/Flexible Motherboard • Domain-Specific: Sensing, Monitoring and Processing Capabilities Dictated by the Intended End-use
Usability	• Privacy • Security • Electrostatic Charge Decay • Resistance to EMI • Hazard Protection • Flame & Directed Energy Retardancy • Physiological Thermal Protection

Durability	• Flexural Endurance
	• Mechanical Strength
	    o Tear
	    o Tensile/Shear
	    o Burst
	• Abrasion Resistance
	• Corrosion Resistance
	• Heat Resistance
	• Electrical Resistance

Shape Conformability (Dimensional Stability)	• Conform to Desired Product Shape • Dimensional Stability during Repeated Use
Maintainability	• Ease of Care • Ease of Mending • Ease of Diagnosing Problems • Launderable (if necessary)
Manufacturability	• Ease of Fabrication • Compatible with Standard Manufacturing Machinery
Connectivity	• Sensors • Processors (Computing, Wireless Communication) • Monitors and Equipment • Power Source (Battery Charging / Changing) • Other *i*-Textile Modules
Affordability	• Material Cost • Manufacturing Cost • Maintenance Cost

5.2 A Framework for Design and Selection of Conducting Fibers

The performance requirements of *i*-Textiles govern the final "design" of the structure including the materials, manufacturing technologies, sensors and processors to be incorporated into the product. Conductive fibers – integral part of the data bus – are at the heart of *i*-Textiles and directly affect not only the performance of the structure but also the realization of the structure in the first place. Figure 70 shows the key factors that must be considered in the selection of conductive fibers to meet the desired performance characteristics of *i*-Textiles (Table 29). They have been grouped into key categories based on the similarity of factors. They include Mechanical/Physical, Chemical, Electrical and Insulation Properties and these are *driven* by the Performance Requirements of the structure. In turn, these material properties are realized through a proper selection of fibers based on the fiber and yarn types, manufacturability, cost and availability, among others. Thus, this framework – resulting from the experimental investigations discussed in previous sections – for selection of conductive fibers should help in two ways:

(i) Design of conductive fibers with specific set of properties; and

(ii) Selection of conductive of fibers for uses to meet specific requirements for different applications of *i*-Textiles.

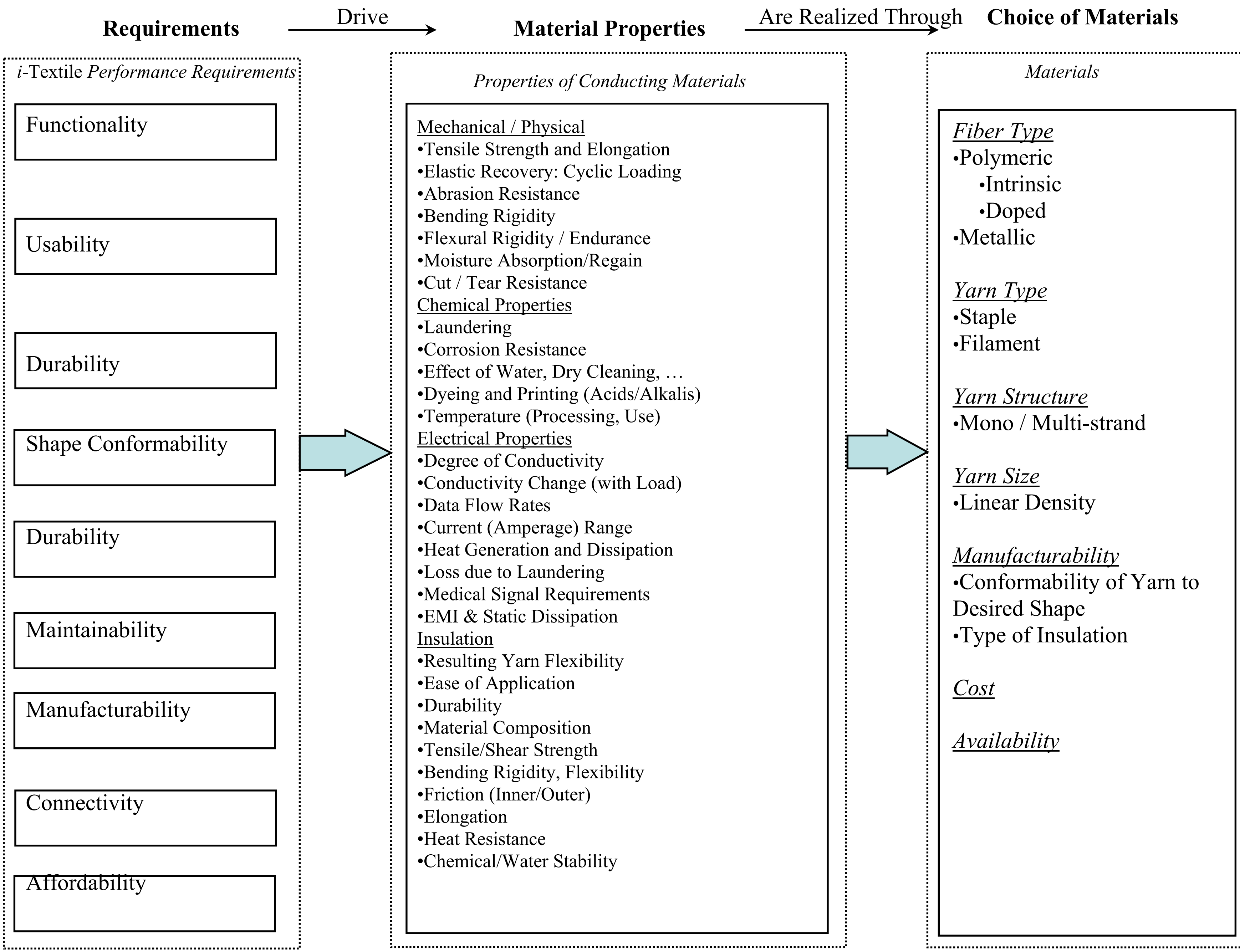


Figure 70. A Framework for Selection of Conductive Fibers for *i*-Textiles

6. PRESENTATIONS AND PUBLICATIONS

During the course of the project, the team members participated in meetings and conferences and also made several presentations on the project accomplishments; these include:

- In September 2001, Dr. Jayaraman made an invited presentation at the FOCUS Seminar held at the Nanyang Technological University in Singapore; the title of his presentation was The Wearable Motherboard: A Flexible Framework for Personalized Mobile Information Processing.
- Ms. Park and Dr. Jayaraman co-authored a chapter entitled Adaptive and Responsive Textile Structures in "Smart Fibers, Fabrics and Clothing: Fundamentals and Applications" (ed. X. Tao) published by Woodhead Publishing Limited, Cambridge, UK in 2001.
- Dr. Jayaraman participated in the Invited Workshop on Nanoscience for the Soldier organized by the US Army Research Office in Research Triangle Park, NC, in February 2001. The focus of the Workshop was on the use of nanoscience and technology, and research initiatives in the area to enhance the military's war-fighting capabilities. The PMIP fabric has a vital role to play in this domain as a "platform" or information infrastructure for the variety of sensors and technologies that can be embedded into it. The results of the Workshop proceedings can be accessed at http://www.aro.mil. One of the outcomes of the

Workshop was the need for a center for concerted activities in nanotechnologies; this has since resulted in the formation of the Institute of Soldier Nanotechnologies at MIT.

- Dr. Jayaraman organized a special session on E-Textiles at CASES 2001, International Conference on Compilers, Architecture and Synthesis for Embedded Systems, held in Atlanta, November 16-17, 2001. He and Ms. Park made an Invited Presentation entitled Textiles and Computing: Background and Opportunities for Convergence at the Conference. Dr. Mackenzie presented an invited paper entitled A Prototype Network Embedded in a Textile Fabric (by Mackenzie, Hanson, Maule, Park and Jayaraman) at the Conference.
- Dr. Jayaraman presented a paper entitled The Wearable Motherboard: A Framework for Personalized Mobile Information Processing (PMIP) (by Park, Mackenzie and Jayaraman) at a Special Session on E-Textiles at the 39th Design Automation Conference in New Orleans, Louisiana, June 10-14, 2002.
- Dr. Jayaraman made an invited presentation entitled The Georgia Tech Wearable Motherboard: The New Class of Adaptive and Responsive Textile Structures (by Park and Jayaraman) at the International Interactive Textiles for the Warrior Conference in Boston, MA, July 9-11, 2002. Both Ms. Park and Dr. Jayaraman also participated in the Workshop following the Conference to identify opportunities for research to enhance the war-fighting capabilities of the soldier.
- Dr. Jayaraman made an invited presentation at the DARPA CyberMedic Workshop on Smart Uniforms, Robots, and Medical Payloads in Cambridge, MA,

September 19-20, 2002. He also participated in the development of the Research Roadmap for Combat Care.

- Dr. Jayaraman delivered a keynote talk entitled Fabric is the Computer: Fact or Fiction? at the Workshop on Modeling, Analysis and Middleware Support for Electronic Textiles (MAMSET) at ASPLOS-X (Tenth International Conference on Architectural Support for Programming Languages and Operating Systems) in San Jose, CA, October 6, 2002.

- Dr. Jayaraman presented a paper entitled The Wearable Motherboard: The New Generation of Textile Structures at the Textile Technology Forum in Charlotte, NC, October 24, 2002.